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The Institution of Electrical Engineers

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The Society of Telegraph Engineers

FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

EDITED BY P. F. ROWELL, SECRETARY

SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C.2

Telegrams: "VOLTAMPERE, PHONE, LONDON." Telephone: TEMPLE BAR 7676.

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[*Continued on page* (*III*) *of Cover.*

THE MICRO-GAP SWITCH

By PROFESSOR W. M. THORNTON, O.B.E., D.Sc., D.Eng., Past-President.

(*Paper received* 19*th March*, 1936, *read before* THE INSTITUTION 17*th December and before the* NORTH-WESTERN CENTRE 15*th December*, 1936, *also before the* NORTH-EASTERN CENTRE 11*th January*, 1937.)

SUMMARY

Alternating-current circuits that can be classed as non-inductive may be broken by a switch in which the separation between the sparking contacts is extremely small. In these micro-gap switches the separation of the contacts on a 250-volt circuit is of the order of 5 thousandths of an inch, and, by the use of a back stop, is not allowed to be more than that distance. The current is interrupted, not by stretching the arc at break, but by the mutual repulsion of electrons that enter the gap from the contacts. Oscillograms are given which show that, when the contacts in these switches begin to open at any point in a half-wave, the current breaks at the next zero point and does not restrike. If broken at zero it persists for the next half-wave. This type of switch is most suitable for the thermostatic control of electric heating systems.

(1) INTRODUCTION

The perfect switch for a normal alternating-current circuit is that which, when it opens the circuit at any point in the half-cycle, prevents the restoration of the arc after the current has fallen to zero. The restriking of the arc depends on two things, the voltage across the gap and the conducting state of the medium in it. In large power circuits the former of these depends greatly on the frequency and amplitude of the oscillations set up across the break. In non-inductive circuits these are negligible and the only field across the gap is that of the circuit voltage. Whether this is sufficient to cause the arc to re-form depends on the length and conductivity of the gap; that is, on the state of ionization of the air, or oil vapour, or of carbonization of the oil itself. The ionization of an air-switch gap is caused by the injection into it of electrons from heated contacts, and by collision of these with molecules under a high voltage-gradient. The emission of electrons at low gradients is solely thermal in origin; it depends only on the temperature of the contacts. If a break greater than the free sparking distance were formed instantly in a non-inductive current-carrying circuit, there would be no arc, for the contacts would not have time to get hot, no electrons would be emitted, and the arc or break spark could not form. There have been many devices to keep the contacts cool at break. These have been mostly concerned with large power circuits, but for relatively small powers and circuits that are in effect non-inductive a form of switch is available that is, according to the above definition, perfect in action.

(2) MICRO-GAP SWITCH AND THERMOSTATIC CONTROL

The thermostatic control of the temperature of electrically-heated water has been made much easier by the invention of the micro-gap switch. Satchwell's arrangement marked a new departure in the automatic control of low- or medium-voltage alternating-current circuits, in particular when they are as nearly as possible non-inductive. The circuits to be broken are in most cases those of the heaters controlling the hot water or air supply for buildings, in which the temperature has to be kept constant within a few degrees. To do this the switch is operated by a bimetallic device, which consists, in the hot-water thermostat, of a non-expanding rod contained within an expanding sleeve. The difference in the lengths is extremely small, about 0·00011 in. for a 12-in. length per degree Fahrenheit. The switch tongue on which the expanding element presses is held by a small permanent magnet until the force upon it overcomes the magnetic pull, and the gap opens suddenly. The length of gap is adjusted by a back stop so spaced that the current, after passing through zero, cannot restrike. The contacts are flat, $\frac{1}{4}$ in. to $\frac{3}{8}$ in. diameter, and are made of silver not only because of its high thermal and electrical conductivity, but because the oxide of silver, if it should be formed by the arc, is electrically a good conductor. On a 250-volt circuit the opening of the gap is about 0·005 in. When the contacts separate the current may have any value from zero to the maximum. It will be shown that the best point to break the circuit is not when the current is zero; but oscillograph records of the current at break show that, at whatever point in the cycle the contacts open, the current stops at the next zero point. This is sufficient evidence of the perfect action of the micro-gap switch.

(3) THEORY OF THE BREAK OF CIRCUIT

(a) General

Any air-gap, however small and highly ionized, has a resistance greater than that of the metal of the contacts. Since these are not perfectly smooth the final separation is at one or more points on the surface. There is a local concentration of current, the density rises, and the metal heats to a temperature depending on the total current broken. From these hot points electrons can leave the metal, and enter the gap, but they do so gently. Their motion within and just outside the metal is according to the Maxwellian law of distribution of energy of particles in collision. This is the first stage in any break of circuit. Once the electrons are free in the gap they are acted on by the field across it and accelerated. The kinetic energy they then acquire is proportional to the product of the field and the gap length. By keeping the latter very small the energy of the electrons in line with the field is diminished, and since the pitting of the

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contacts is due to the energy of bombardment by the current stream it also is greatly lessened.

If there were no voltage gradient in the gap any electrons in it would repel one another and be expelled sideways as if there were a miniature explosion. This can in fact be seen to occur. It is the special and characteristic feature of micro-gap breaks that the current is always broken only by a lateral spread of the arc through mutual repulsion of its elements, not by stretching the arc.

When there is no back stop and the arc lengthens as far as the voltage of the circuit can maintain it, further physical actions come into play. The lateral spread may be checked by the attraction of the current elements forming the arc, and the current itself is reduced by the influence of its increasing resistance in the circuit. The arc at large breaks is pear-shaped, with the blunt end at the cathode. The attraction between electrons moving in the same direction only balances their mutual electrostatic repulsion when their velocity is equal to that of light; so that the pear-shaped long arc depends more on attenuation than on a "pinch" effect.

(b) Analysis in Terms of Electrons

The magnetic field at a distance r at right angles to the line of motion of a current i, due to any element δs of it, is given by $H = i\delta s/(cr^2)$, where c is the ratio of the electric units, or the velocity of light. In the case of two electrons moving in parallel with velocity v, we may write

$$H = \frac{i\delta t}{cr^2} \cdot \frac{\delta s}{\delta t} = \frac{\delta q \, . \, v}{cr^2}$$

or, here,

$$H = \frac{ev}{cr^2}$$

where e is the electronic charge, contained in the element δs. The element of parallel current at a distance r is also $i\delta s$. The force on this element in the field H is $Hi\delta s$, or Hev/c. This is the force of attraction between two moving electrons considered as elements of parallel currents. The force of repulsion between them is e^2/r^2. These forces are equal when

$$\frac{e^2}{r^2} = \frac{e^2v^2}{r^2c^2}$$

or when

$$v = c$$

The charge of an electron in electrostatic units is $4 \cdot 7 \times 10^{-10}$. The electron mean free path, l, in air at normal temperature and pressure is $4\sqrt{2}$ times the gas kinetic mean free path. The latter is $9 \cdot 5 \times 10^{-6}$ cm. Thus $l = 5 \cdot 35 \times 10^{-5}$ cm. Take, for instance, the case where the electrons are one mean free path apart, i.e. let $r = l$. The force of repulsion is given by

$$\frac{e^2}{r^2} = \frac{(4 \cdot 7)^2}{10^{20}} \times \frac{10^{10}}{(5 \cdot 35)^2}$$

or

$$F = \frac{0 \cdot 77}{10^{10}} \text{ dynes}$$

The electric field F/e between the charges is then

$$\frac{0 \cdot 77}{10^{10}} \times \frac{10^{10}}{4 \cdot 7} = 0 \cdot 164 \text{ e.s.u.} = 49 \cdot 2 \text{ volts per cm.}$$

This is much too small for ionization by collision to occur by mutual repulsion at atmospheric pressure. Since the mass of an electron is so small, 9×10^{-28} gramme, the acceleration even in so low a field is high, and the velocities acquired due to mutual repulsion would be high if it were not for the presence of the molecules of air which absorb their energy on collision, though without ionization.

The pressures in condenser-discharge sparks have been measured and found to be many atmospheres. At the break of circuits such as those now considered there is also a pressure pulse, to be observed if the break is made in a confined space. There can be little doubt, therefore, that the physical action in a micro-gap break is a sideways repulsion between the electrons of the arc, and collision between them and the molecules of air in the gap, that blows out the air and has all the features of a miniature explosion.

(c) Effect of Cooling of Contacts

The rate of extinction of the arc depends also upon the cooling of the contacts. The conductance σ of unit area of the gap may be taken as approximately proportional to the number of electrons in it at any instant and therefore to the current density, i_1. The rate of heating P_1 is then $ki_1^2/\sigma = k_1 i_1$. If the current i is broken near its maximum value, it is for a moment sensibly constant. Thus

$$P_1 = \frac{k_2 i}{\pi R^2} = \frac{k_3}{R^2}$$

where R is the radius of the arc; or the intensity of heating falls off as the inverse square of the radius of the arc as it expands. If the rate of radial expansion is proportional to the rate of heating in the space occupied by the arc, P_1 varies inversely as $(\text{time})^{\frac{2}{3}}$. At the moment of formation the rate of heating may be high, but it falls off with time rather faster than according to a hyperbolic law. If the first heating of the contacts is fully established in a thousandth of a second, it is about halved in the next thousandth. The rapid diminution of the rate of heating of the contacts due to the mechanical forces in, and expansion of, the arc, quickly reduces them to an electrically inert state and the arc goes out.

(4) OPERATING CHARACTERISTICS OF MICRO-GAP SWITCH

The electric strength of air between parallel surfaces is such that an alternating voltage of 250 volts r.m.s. or 350 volts maximum will not break down a gap of 0·005 in. For a 500-volt circuit, 0·01 in. is required. These define the gap lengths that may be used. Even with the latter relatively large gap a circuit carrying 100 kW has been interrupted without the arc restriking or the contacts pitting. How far it may be possible to apply the lateral-repulsion action to higher-voltage circuits remains to be seen. The advantage of this type

of switch would appear to be confined to low-voltage non-inductive alternating-current circuits, where, as in thermostats, the operating movement is small.

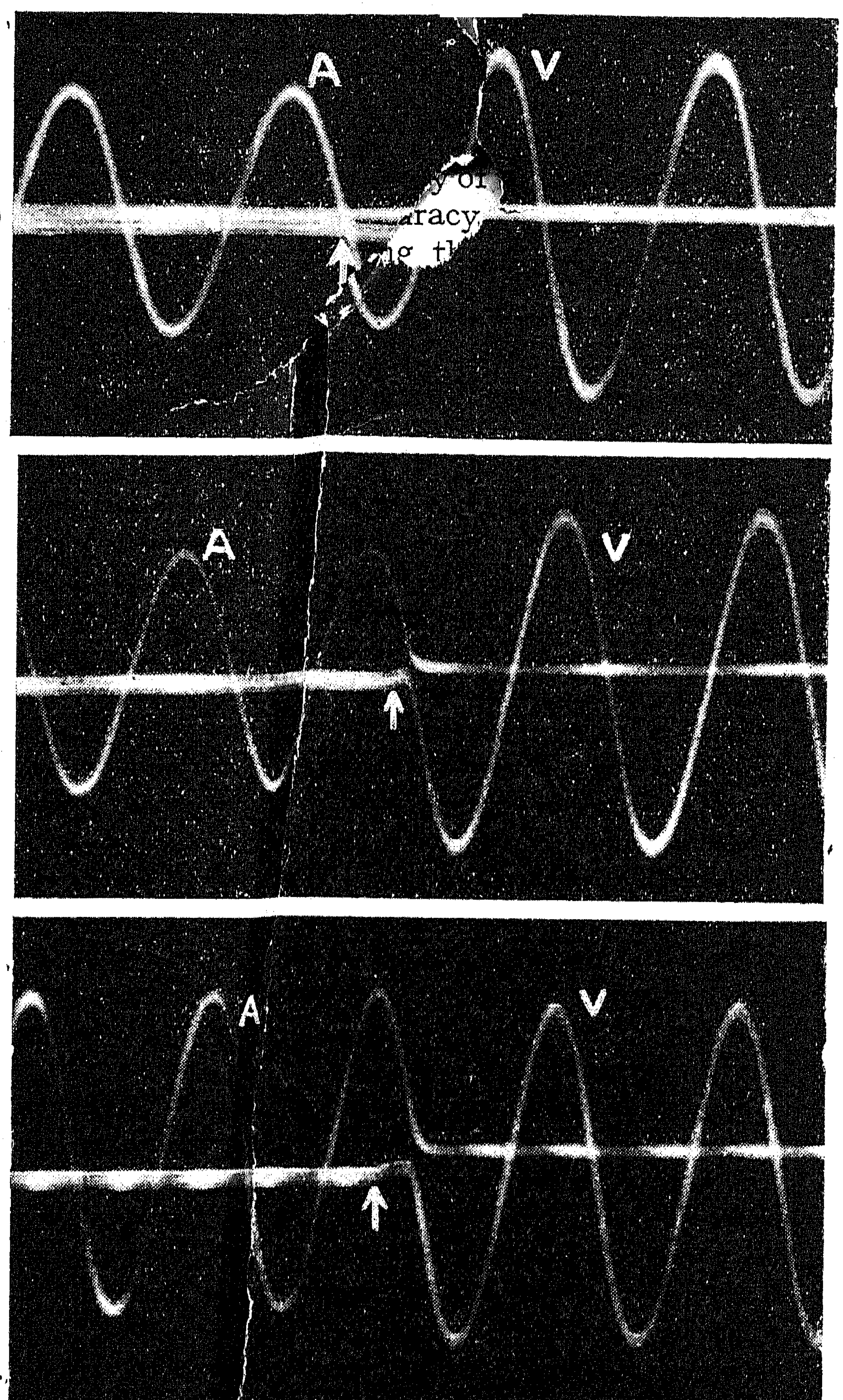


Fig.—Oscillograms showing relation between current and voltage.

The oscillograms reproduced in the Figure show the relations of current and voltage in the gap in three typical cases: (*a*) when the circuit opens as the current passes through zero, but does not break until the next zero; (*b*) when the circuit opens at 45° before zero, the current breaking at zero; (*c*) the circuit opening when the current is a maximum, the current breaking at zero. The voltage in each case was 250 volts and the current 15 amperes. The time scale is in each case from left to right. The arrow indicates the point where the switch opens.

In (*a*), the small voltage across the gap is nearly uniform during the half-period, rising slightly, and reversing to a full maximum when the current stops. The change from the current curve to the voltage curve is shown only by the increase of amplitude after the break. In (*b*), the voltage begins to rise at the moment the circuit opens, about halfway between the maximum and zero, but reverses as the current reaches zero. In (*c*) the point where the rise of voltage begins is midway between the zero points, i.e. at the maximum value of the current.

These oscillograms show that the best place to break a non-inductive circuit is not at zero current but in the quarter-period before a zero point. There must be some electrons in the gap to repel one another and to break the circuit.

It is possible to break nearly non-inductive currents such as those in radiators without a destructive arc even when the motion is slow, as by withdrawing a plug from a socket; but when a parallel gap is set to non-striking distances, though not lengthened indefinitely, the breaking action is by a lateral repulsion of the electrons in it and not by stretching the arc.

An interesting point was observed by Mr. R. Bruce, who took the oscillograms. In most cases the gap began to open at the moment the current reached a maximum value, always of the same polarity. This suggested that there might be, in addition to the thermal expansion, an electromagnetic action causing the gap to open. Mr. Bruce found then that the switch when delicately set would operate with large currents without any expansion of the thermostat elements. On inquiry it was found that this effect had been observed before, though not explained. It is clearly due to a resultant weakening of the magnetic hold of the permanent magnet on the soft iron armature. The magnetic field of the current flowing through the contacts over the permanent magnet to the terminals deflects the field away from the poles and weakens the resultant pull. A switch of this type therefore breaks automatically on overload and is an additional safety device in the circuit.

[The discussion on this paper will be found on page 468.]

RESTRIKING VOLTAGE, AND ITS IMPORT IN CIRCUIT-BREAKER OPERATION

By H. TRENCHAM, Member, and K. J. R. WILKINSON, B.Sc., Associate Member.

(*Paper first received 3rd June, and in final form 10th September*, 1936; *read before* THE INSTITUTION 17*th December, before the* NORTH-EASTERN CENTRE 23*rd November, and before the* NORTH-WESTERN CENTRE 15*th December*, 1936.)

SUMMARY

Restriking voltage and its principal significance are described, and the problem of relating these to circuit-breaker operation in power systems is stated. An instrument for showing inherent restriking-voltage characteristics is described in some detail, reasons being given for the leading features adopted; and the method of operation is outlined. The scope of possibilities in system investigations and in circuit-breaker development is indicated. A short appendix deals with design of the instrument.

(1) INTRODUCTION

Restriking voltage is the term applied in this country to the oscillations of voltage which occur between the terminals of a circuit breaker following a zero value of the current wave during circuit interruption by the breaker. It is a term describing the manner in which the recovery voltage arrives at the breaker terminals.

The form of restriking-voltage curve depends primarily, and for its inherent characteristics, on the electrical constants of the circuit, but it will be influenced also by the circuit breaker itself and its manner of functioning. The voltage may be oscillatory, having one or more frequencies and with almost any degree of damping.

The amplitude of the curve is governed mainly by the magnitude of the recovery voltage and by the power factor of the circuit, i.e. the instantaneous value of the recovery voltage at the time of current zero, but again it may be influenced in a number of ways by the operation of the breaker; thus it would be affected, for example, by current suppression.

It is accepted that the important attributes of restriking voltage in circuit-breaker operation are amplitude and rate of rise, since their possible action is to overcome insulation in the gap between the switch contacts and so cause the arc to restrike. In assessing a value for the severity of the restriking voltage, two modes of description have been utilized, viz. rate of rise in volts per microsecond, and principal frequency of the circuit; but neither of these provides a satisfactory specification, because no account is taken of the amplitude. Thus a comparatively moderate rate of rise, if maintained, may be more troublesome to a circuit breaker than a very high rate produced for only a short time. It has been suggested that the rate of rise may be more usefully expressed as the slope of a tangent to the curve of restriking voltage at a point above some arbitrary minimum value, and drawn through zero. Whilst this may contain the basis of a useful compromise, there is quite insufficient evidence from which to conclude what minimum value should be chosen for any given type of breaker. Much less is it possible to say that the same value could be correctly applied to all breakers with their various arc-extinguishing characteristics.

(2) THE PROBLEM

There is thus a major problem involved in determining the effect of form and amplitude of restriking voltages on circuit-breaker operation.

A great deal of attention has already been devoted to the analytical study of restriking voltage, mainly to afford means of comparison between service and test-station conditions. Usually the conditions in test stations are more severe than those in service, but while this is as it should be, the facts outlined in the introduction show that simple figures purporting to represent rate of rise of recovery voltage on test cannot as yet adequately express the severity of duty. Knowledge of restriking voltages in power systems is very scanty and, so far as the authors are aware, no data exist on the comparative behaviour of a given breaker in differing system conditions or of breakers of different characteristics under the same system conditions.

Thus, while recognizing the importance of restriking voltage in tests carried out on circuit breakers, testing authorities feel that it is advisable to withhold definite comments which would give the appearance of quantitative worth and thus create false impressions as to relative severity values.

Restriking-voltage characteristics calculated from circuit constants aim at showing the true value inherent in the circuit, but those recorded by cathode-ray oscillograph taken on short-circuit tests differ from calculated values for a number of reasons. These complications are mainly:—

(1) The effect of arc resistance, particularly when a long arc has been drawn;
(2) The manner of the build-up of insulation value in the arcing space at current zero, i.e. residual or post-arc conductivity;
(3) The action of arc-control devices in effecting current suppression.

In attacking our main problem, therefore, it is evident that its solution is virtually impracticable unless we have a means of determining easily and accurately the voltage/time curve of restriking voltage inherent in any desired part of a system.

Given such a means, it is possible to examine system conditions with a view to their comparison and co-ordination, and it is obvious that without such facility it would be impossible to obtain information in sufficient quantity to enable accurate conclusions to be drawn.

(3) THE RESTRIKING-VOLTAGE INDICATOR

Some account has already appeared in the technical Press describing the main features and principle of operation of a restriking-voltage indicator designed and built by the organization with which the authors are connected.

These matters will, therefore, be recounted only very briefly for the sake of leading naturally to a more detailed statement of the theory of the device, the sources of error, and the order of accuracy which can be achieved.

The possibility of making this instrument was suggested originally from a consideration of the results achieved with recurrent surges on a high-vacuum glass cathode-ray oscillograph tube, and the facility with which these recurrent surges could be generated by means of a mercury thyratron and repeated at very accurately-spaced time intervals. By generating recurrent surges many of the difficulties associated with high-speed recording are eliminated, because if surges of the desired shape are produced in rapid succession and associated with a suitable recurrent time-sweep of the cathode ray, the effect is that of a permanent image which may be observed or photographed at leisure. The inherent restriking-voltage characteristics of a system involve times which are short compared with a power-frequency interval, so that it becomes possible to generate recurrent surges as frequently as 50 times per second.

(a) Principle of Operation

In order to generate a wave of the desired restriking-voltage form, it is necessary to do one of two things. Either an ideal switching operation must be simulated, i.e. a current of the form $i = I \sin \omega t$ must be removed from the system, or, alternatively, current of the same form must be injected into the system whose terminals are the open breaker. The latter method, amongst other advantages, requires access to the system at one point only, and was chosen as the more suitable one. It had been previously suggested* but so far as is known the idea had never been applied.

The current surge which, starting from zero, shall thereafter follow the form $i = I \sin \omega t$, must follow this form with sufficient accuracy for a period of some hundreds of microseconds, and this despite the impedance of the system into which it is to be injected. Use is therefore made of a " constant current " circuit, i.e. one in which the impedance of the generator is high compared with the load or system impedance.

Theoretically an inductance to which alternating voltage is applied at a crest value not only generates a current surge of the correct form but can also give the desired " constant current " or high-impedance characteristic. Unfortunately, a physical inductance has the disadvantage that it cannot be made sufficiently free from self-capacitance to avoid giving rise to initial distortion of the current surge. In the instrument here described, use has therefore been made of a mutual inductance wherein surge current is derived from a secondary winding which is electrostatically screened from the primary winding.

* C. Dannatt and S. E. Goodall: " Circuit Interruption," *Electrician*, 1935, vol. 114, p. 539.

(b) Arrangement of the Instrument.

The general diagram of Fig. 1 shows that power is supplied to an auto-transformer which, in turn, feeds:—

(1) The cathode-ray tube.
(2) The time-scanning coil and surge-releasing transformer.
(3) An amplifier circuit, and
(4) The current-surge generating circuit.

Connections are so arranged that a current surge is initiated by the thyratron during those half-cycles in which the cathode-ray tube is operative.

(c) The Cathode-Ray Tube.

This differs from a standard Ediswan type AH tube in that only one pair of deflector plates is provided and leads from these are brought to terminal caps in the walls of the tube in order to reduce capacitance loading of the amplifier. The deflector plates are so proportioned as to give a sensitivity of about 3 volts per mm. at a beam accelerating voltage of 3 500.

(d) The Scanning Coil.

Recurrent movement in the " time " direction is derived magnetically from a scanning coil excited from the 50-cycle supply.

Given a reasonably low power factor, the desired maximum and linear velocity of sweep can be obtained so as to coincide with the crest value of applied voltage and the instant of surge generation. In order to ensure accurate superposition of successive images it is necessary to provide some synchronizing means between the time-sweep circuit and surge generator. For this duty, use is made of a saturable-core peaking transformer of which the primary is excited by the scanning current.

(e) The Amplifier.

An impracticably large surge generator would be necessary in order to give restriking voltages with amplitude sufficient to operate a cathode-ray tube directly, so a single-stage push-pull amplifier is incorporated, which gives a gain of about 75 and uses a maximum input of 3 volts. The amplifier circuit is given in Fig. 1, and its behaviour is shown by the sensitivity/frequency and gain/frequency curves of Fig. 2. Some improvement in frequency response is obtained at high frequencies, by parallel compensating condensers in each grid/cathode circuit.

(f) The Current-Surge Generator.

Essentially the surge generator comprises a mutual inductance L_1, M, L_2 (Figs. 1 and 3*a*), together with a thyratron T, by means of which the primary is connected to the supply at each positive voltage maximum. Factors which control the form of the mutual inductance are discussed in the Appendix. In the present instrument there are two available primary and four secondary coils—two to each primary—making four possible ranges. Each range is given further flexibility by applying either of two voltages to the primary. In this way restriking-voltage images are obtained of which the voltage dimension is

roughly between 3 and 6 cm. throughout a band of system impedance extending from 0·05 to 20 ohms as measured at 50 cycles.

(g) Calibration.

In recording restriking-voltage forms it is necessary to apply scales from which voltage and time can be interpreted. The value of the time scale can readily be obtained by passing the current surge through a model resonant circuit of low loss and known frequency and by photographing or measuring the resulting oscillatory trace.

To ascertain the voltage scale is not quite so straightforward, but there is no serious difficulty in assigning a value to it. Any oscillations of the restriking voltage will start from zero, swing about as governed by the circuit constants and damping, and come to rest on the power-frequency wave of recovery voltage. If, therefore, a reading of the instrument can be taken following the conclusion of the disturbance, this will give the recovery voltage and so afford a scale by which voltages may be measured. Such a reading can be facilitated, if necessary, by introducing an artificial damping resistance across the breaker terminals in order to reduce the restriking oscillations, and so cause the trace to merge more quickly into the relatively constant recovery-voltage value.

(h) Accuracy.

If a surge current of the form $i \propto t)_0^\infty$ is passed into a parallel resonant circuit L, C (Fig. 3*b*), it can be shown that the consequent voltage is of the form $B(1 - \cos qt)$, where q is $2\pi \times$ frequency of the circuit, and B is independent of t and C. Thus the amplitude should vary between zero and a constant value $2B$. But this applies to a surge current of type $i \propto t)_0^\infty$, whereas the desired surge current is of form $i \propto \sin \omega t)_0^\infty$, where ω is $2\pi \times$ power frequency. However, at 50 cycles the error from this cause is less than 0·5 per cent after 500 microseconds, so that we may conveniently judge the instrument behaviour as though for a linear surge.

The performance of each range of the instrument has been examined by comparing relative deflections of the image on passing a surge current through low-loss fixed inductances, shunted by a variable capacitor to give frequency variation. Results of this examination—which naturally include errors associated with the amplifier—are shown for the four ranges of the instrument in Fig. 4 (*a*, *b*, *c*, and *d*).

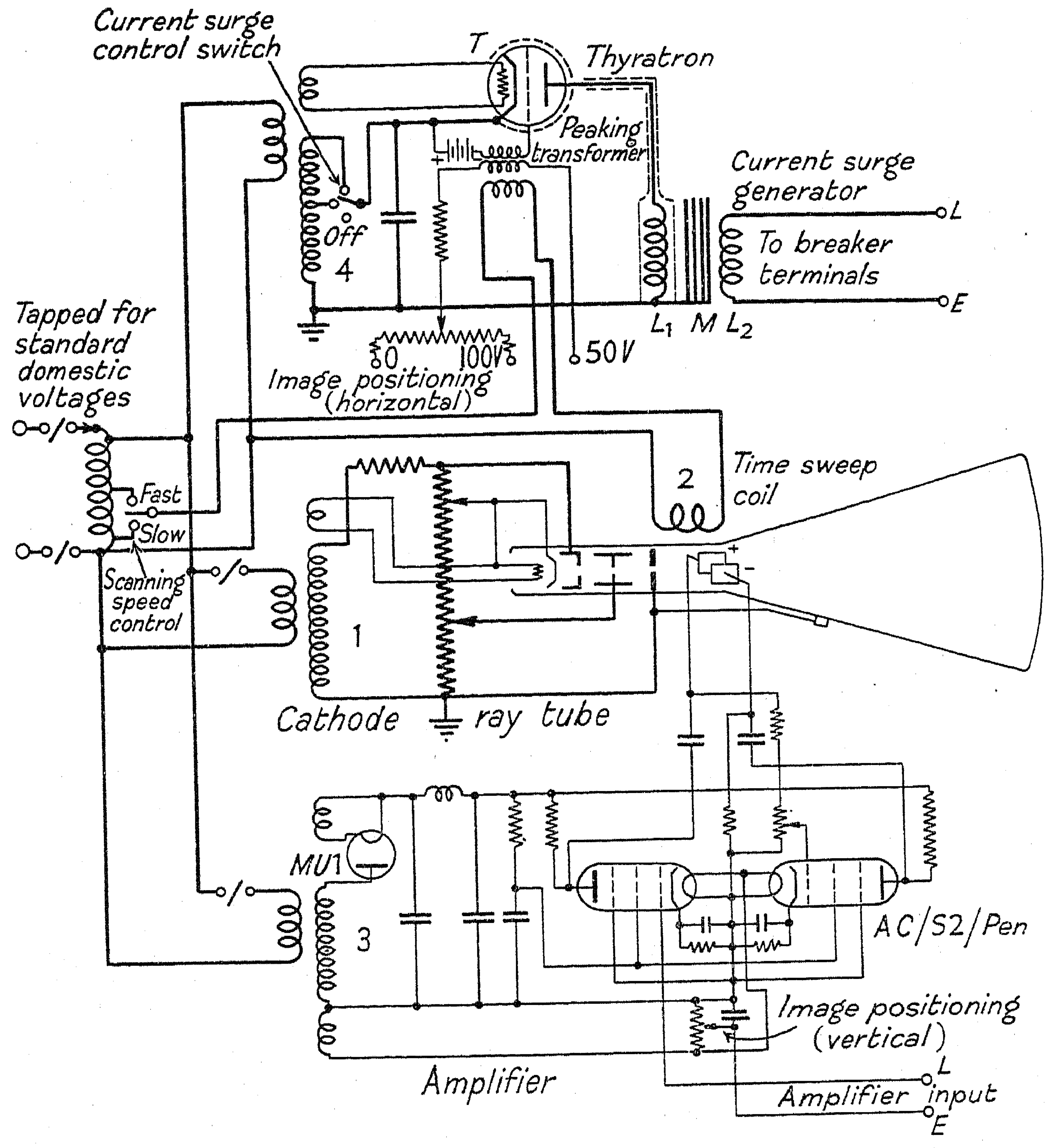


Fig. 1.—General circuit diagram of the restriking-voltage indicator.

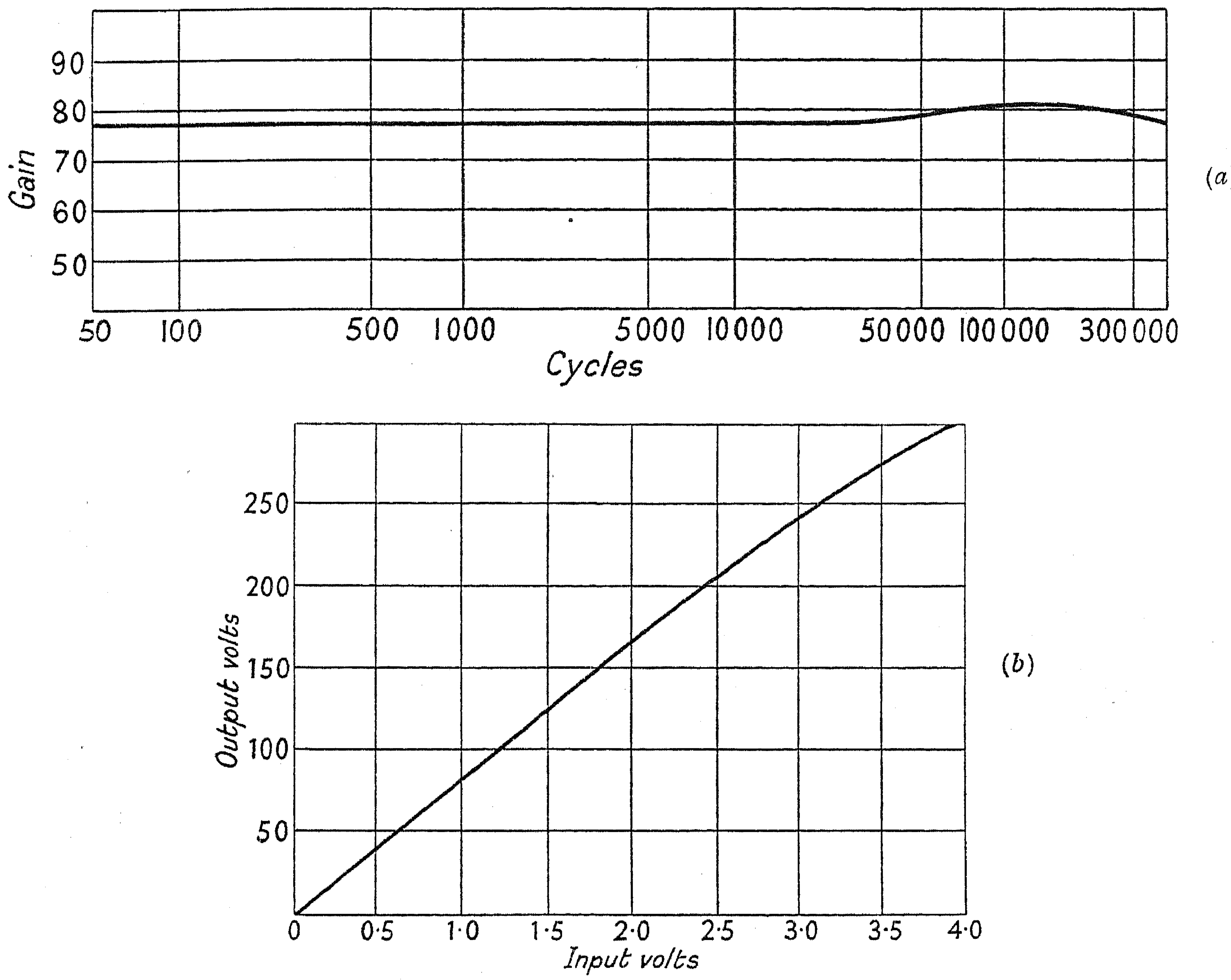


Fig. 2.—Characteristic curves of the amplifier unit.

These results indicate relative values of the first maxima and first minima, but where subsequent maxima or minima have greater errors those values are also recorded. The upper limit of frequency, which will be discussed in the Appendix, is clearly indicated by these results. Below this, frequency response of the instrument is constant mostly within 10 per cent. As a further check that the instrument functions correctly, a model circuit, shown in Fig. 5, has been explored by range 2, and the resulting oscillogram is given in Fig. 6. Each of the components of this circuit was measured separately, and the circuit behaviour was calculated for the case of a current of form $i \propto t)_0^\infty$. The calculated value is drawn to an arbitrary voltage scale in Fig. 5. It will be seen that the oscillogram agrees closely with the calculated values.

There are two ways in which the instrument may be limited in its usefulness. Firstly, there are frequency limits above which it becomes impracticable to build a surge generator of the mutual-inductance type. Fortunately, experience with test-station plant suggests that this limitation is not a serious one throughout the ranges of the instrument. These cover 50-cycle impedances from 0·02 to 20 ohms.

Secondly, owing to the relatively low voltage impressed upon the system under examination, stray interference voltages may affect results. This form of interference has been met in positions near a large long-wave radio transmitter, but no such interference has occurred in the test station where the instrument is in use.

(j) Operation.

Phase control of the peaking transformer allows the image to be moved in a time direction, and a switch labelled " fast " and " slow " controls the voltage applied to the scanning coil, giving speeds of 0·86 mm. and

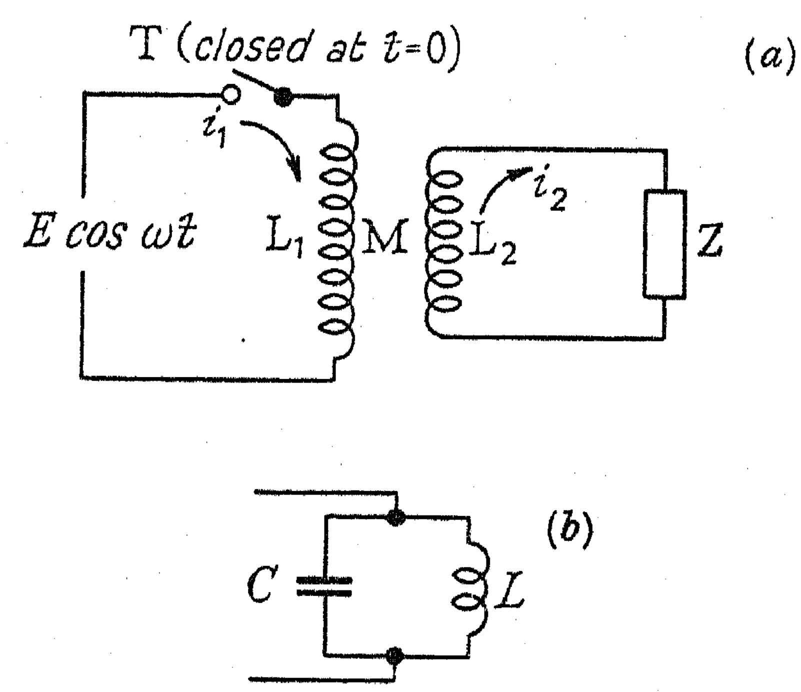


Fig. 3.—Elementary diagram of surge generator and load circuit, neglecting generator resistances.

0·39 mm. per microsecond on the fast and slow positions respectively.

An auxiliary resonant timing circuit is available which gives a 100-kc wave when a surge current is applied to it.

A switch marked " full," " half," and " off," applies either of two voltages (via the thyratron) for generating the recurring surge currents. An amplifier bias control permits use of the optimum part of the amplifier characteristic, and finally two potentiometers in the cathode-ray tube circuit give control of spot focus and intensity.

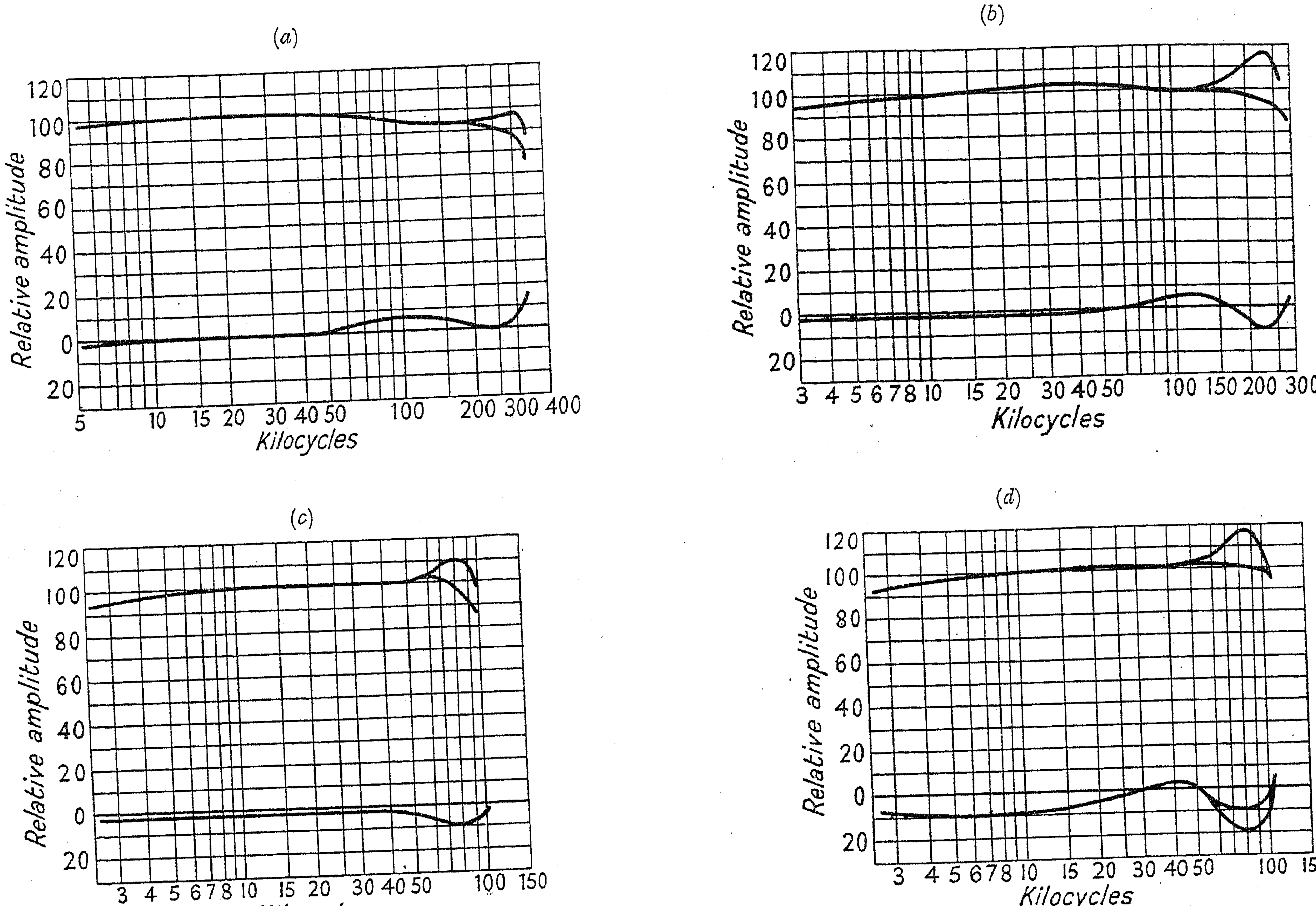


Fig. 4.—Frequency/response characteristics of the restriking-voltage indicator.

(a) Range 1 (0·05 to 0·2 ohm).
(b) Range 2 (0·2 to 1·0 ohm).
(c) Range 3 (1 to 5 ohms).
(d) Range 4 (5 to 20 ohms).

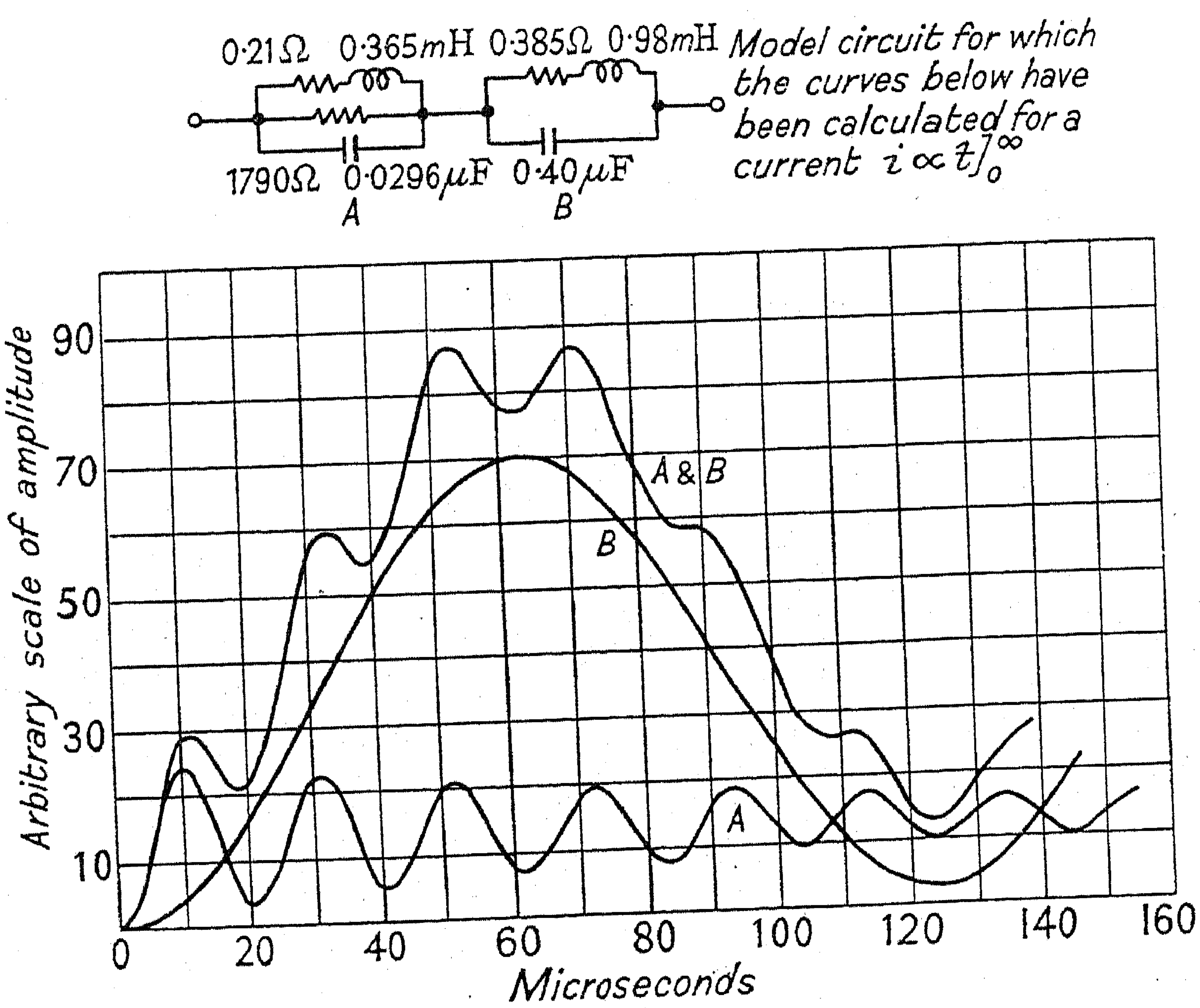
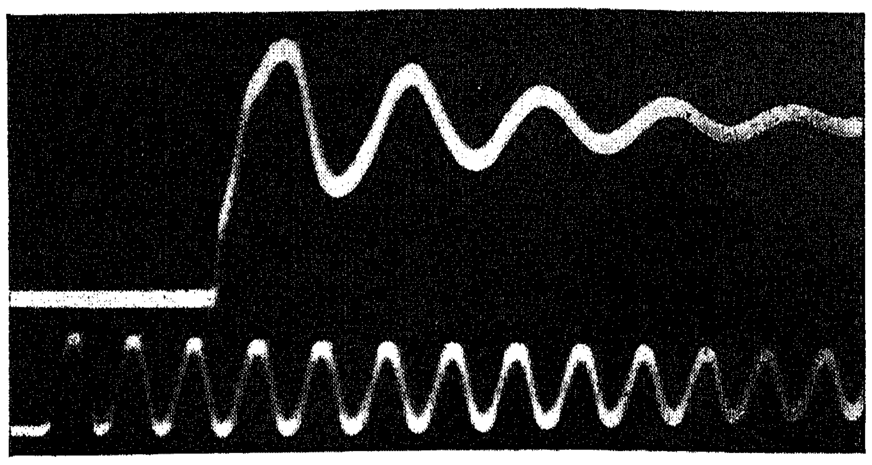
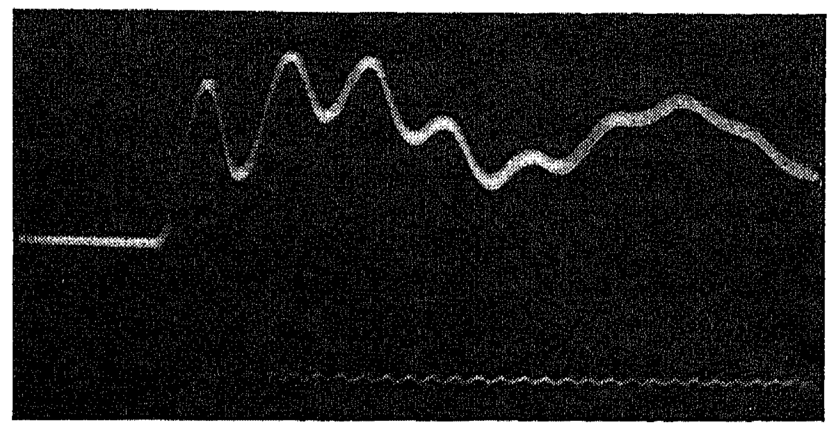


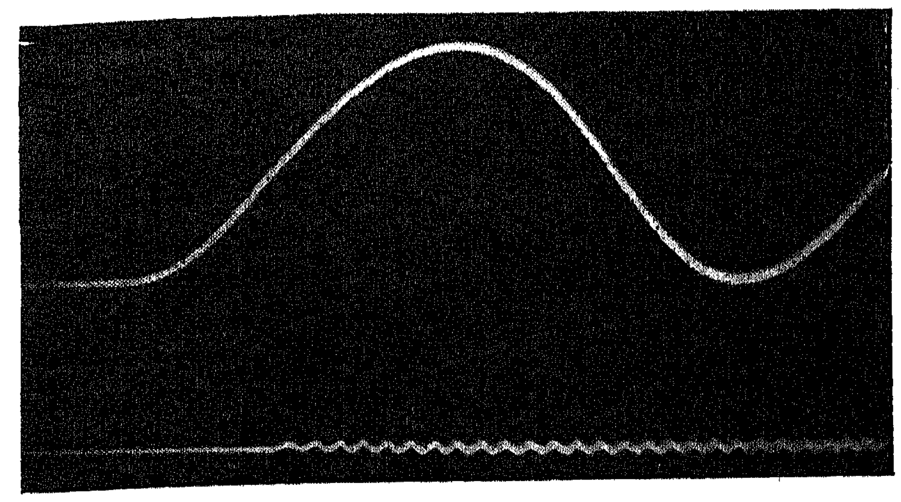
Fig. 5.—Calculated behaviour of a circuit, the corresponding oscillograms for which are indicated in Fig. 6.



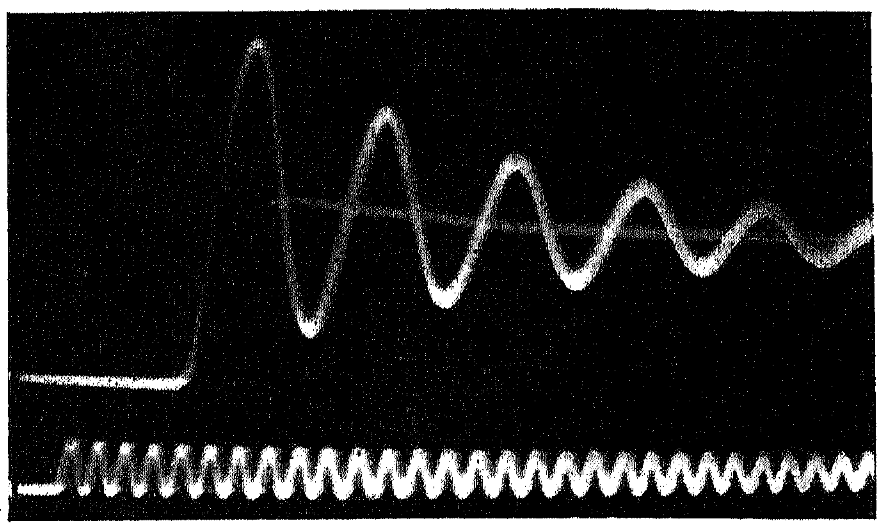
A



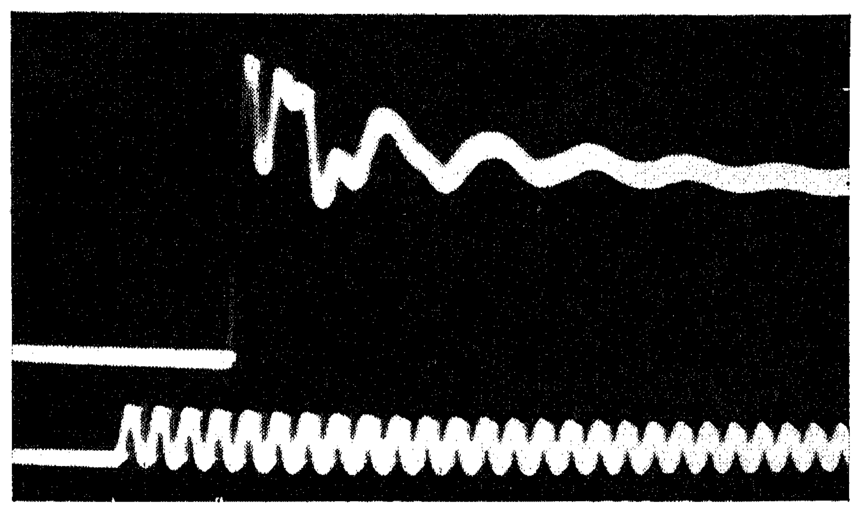
B



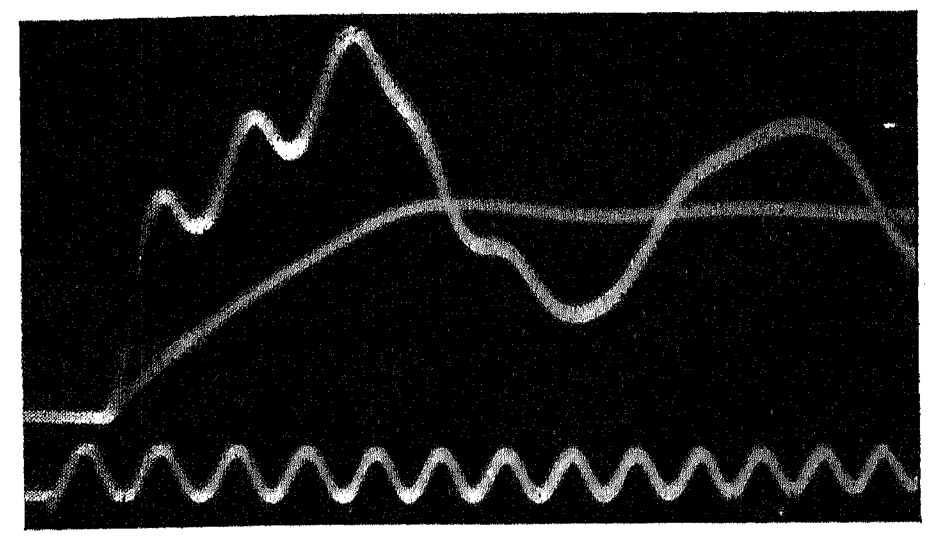
C



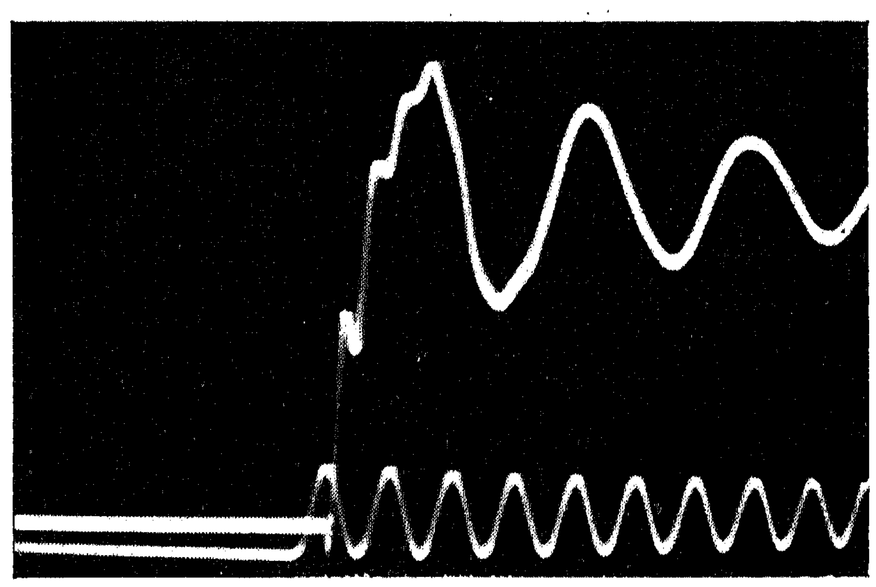
D



E



F



G

Fig. 7.—Some Typical Restriking-Voltage Curves Recorded in a Testing Station

It may be of interest to note that most of these restriking-voltage waves are amenable to a rough classification in terms of:—

(*a*) Maximum amplitude reached, expressed as a percentage of the theoretical maximum possible.

(*b*) Time in microseconds to reach that amplitude.

This classification disregards the shape of the path by which maximum amplitude is reached. Approximate measurements of these quantities are given below.

Fig. 7	Condition	Maximum amplitude (per cent)	Time in microseconds to reach maximum
A	Test generator alone	66	11
B	Test generator with reactors only	72	64
C	Test generator with reactors and added capacitance ..	—	—
D	Normal test circuit with breaker, 11 MVA at 6·4 kV ..	96	22
E	Special test circuit with breaker, 251 MVA at 10·3 kV ..	75	6·8
F	Normal test circuit with breaker, 288 MVA at 11 kV ..	92	33
G	Normal test circuit with breaker, 910 MVA at 11 kV ..	66	16

The input to the instrument is approximately 2 kVA, single phase, at 50 cycles.

A suitable camera is mounted in position for taking photographs, and the image is sufficiently steady for exposure to be given.

(4) SCOPE FOR INVESTIGATION

As already explained, the instrument is designed to indicate the shape of the transient restriking voltage wave which is incidental to, or inherent in, any circuit conditions, and these indications may be observed, traced, or photographed.

The current surges are applied to dead circuits, which must include all those inductances, resistances, and capacitances, which, together, determine the restriking-voltage transient for the particular fault condition under examination. Connections may be arranged to represent, for example, interruption of the first phase to

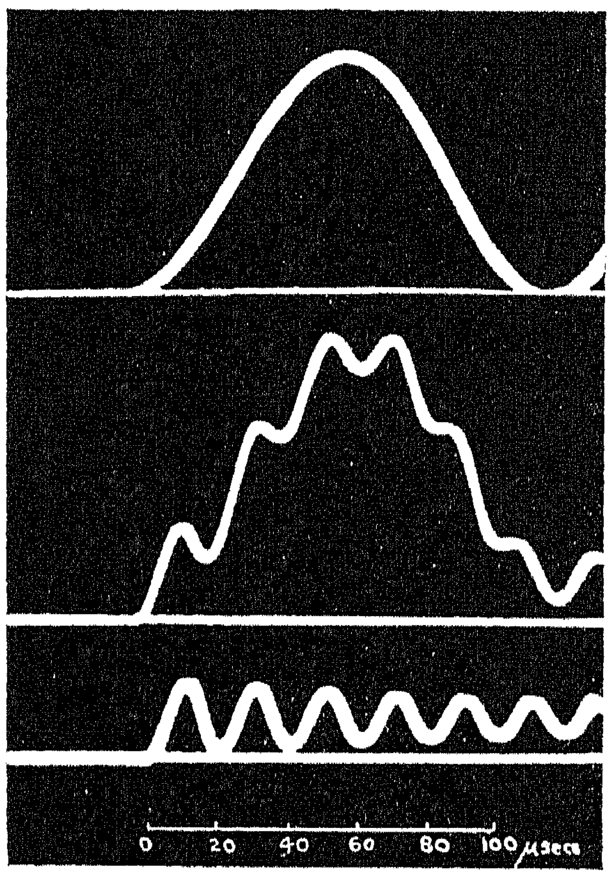


Fig. 6.—Reproduced from an oscillogram taken with range 2 of the instrument applied to a model circuit. The upper curve is due to the right-hand part, the lower to the left-hand part, and the centre to both parts, of the circuit shown in Fig. 5.

clear, while the others are bridged to represent low arc resistances. With the first phase opened, the conditions on the others may be examined in turn. The inclusion or exclusion of feeders, transformers, and machines, can be arranged according to the operating conditions of the system under investigation.

In order to ensure that the test circuit is dead it is necessary that any machines included shall be stationary. This is justified because, during the time intervals covering the restriking-voltage transient, a running machine is, in fact, almost stationary (100 microseconds represents 1·8 electrical degrees at 50 cycles). Flux linkage may be different, however, in different rotor positions, and iron saturation effects may be encountered. Whilst these effects have not yet been fully explored, a limited number of tests have been taken on a typical test generator having a cylindrical rotor with heavy damper windings. These tests were made with the machine only in circuit so that any variations would have a maximum effect, and the results are summarized as follows:—

		per cent
Rotor and stator poles co-incident.		
No excitation.	Frequency reading	100
With normal excitation.	,, ,,	104
With virtual saturation.	,, ,,	105
	Maximum difference	5

Excitation at virtual saturation.		
Rotor and stator poles co-incident.	Frequency reading	105
Rotor and stator poles displaced 75°.	,, ,,	110
Rotor and stator poles displaced 90°.	,, ,,	111
	Maximum difference	6

Where the machine alone supplies the principal components of the circuit constants it is evident that excitation is desirable, and when further accuracy is desired the rotor should be set in the position representing maximum flux change, i.e. corresponding to restriking voltage at zero power factor.

(a) Power-System Investigations.

In power-system investigation the restriking-voltage indicator provides a means of obtaining information which is urgently needed. Its use can impart knowledge of those restriking-voltage conditions which apply under any normal scheme of operation, and, further, can confirm the adequacy of any step which might be taken on theoretical grounds to ensure that the layout does not contain needlessly severe conditions.

It is desirable that a large number of representative system conditions be explored as early as possible, so that they may be used to establish the basis for recognized reference conditions.

In this connection the effect of capacitance in the neighbourhood of the circuit-breaker terminals in reducing the rate of rise of restriking voltage is well recognized, but more detailed knowledge of its practical value in system operation is necessary.

(b) Test-Station Investigations.

Typical conditions as determined by a knowledge of system behaviour could, by means of the restriking-voltage indicator, be reproduced in a test station, and relative performance of breakers examined under these conditions and under others of varying severity to establish recognized margins of safety.

The applications in test-station work are considerably wider in their range of possibilities than a mere checking against working conditions. The ability of the instrument to show the inherent conditions uninfluenced by the factors mentioned earlier in this paper will provide the designer with means to ascertain the effects produced by various arc-control devices and of changes which are introduced in the course of development. This will be rendered possible by a comparison of the instrument reading with that of the cathode-ray oscillograph now normally employed in short-circuit testing, since the latter includes these effects superimposed upon the inherent restriking voltage. Without any accurate

knowledge of inherent conditions, every investigation starts off with the disadvantage of an indefinite basis.

As already stated, the severity of any given form of restriking-voltage wave cannot, as yet, be accurately assessed. Indications are already in evidence that most of the proposals of a simple character for dealing with this factor will fail to give a proper indication of its worth, and that there is still an important gap in our knowledge which, on several occasions, has led to unexpected results.

The restriking voltage is, of course, only one of the two main and recognized factors, the other being the rate of growth of electric strength in the arcing space; and it may so happen that the unexpected results referred to in the previous paragraph are merely a manifestation of some unusual conditions in the other factor. Attempts are being made to evaluate the resistance conditions in the arc space, but the problem to be studied is an exceedingly difficult one. The phenomena are very short in duration and do not recur, so that investigations are limited to actual test interruption. It is all to the good that we have now a means of measuring the one factor in our reactions, and this will undoubtedly assist in the study of the other, though it is too early as yet to prophesy as to the possibilities.

Some typical restriking-voltage curves recorded in a testing station are reproduced in Fig. 7 (see Plate facing page 464).

(5) CONCLUSION

The need for taking into account quantitatively the rise of restriking voltage in circuits and circuit breaking is already well recognized, and certain tentative schemes for doing so have been discussed amongst designers and others.

Definition of this factor, either by reference to a natural frequency, or to a rate of rise of voltage per microsecond, are both basically incomplete and, therefore, unsuitable unless some added information is given.

The form of restriking-voltage waves which are met in practice is complicated, and the number of different possible forms infinite. Therefore, it would not be easy to agree upon any standard representative form, bearing in mind that such a form must also be capable of easy reproduction in test stations.

The performance of any breaker is the outcome of the two contending factors, restriking voltage and the characteristic of insulation build-up, so that any statement regarding severity of restriking voltage implies a knowledge of the second factor. Thus, a rational comparison of severity between any two restriking-voltage waves is impossible without reference to some characteristic, either known or implied, of breaker vulnerability. Until this knowledge is available, therefore, it is not logical to attempt to define restriking-voltage severity.

Lacking any direct means of measuring the rate of insulation build-up within a breaker, it is now rendered possible by means of the restriking-voltage indicator to plan a programme of tests in which, by separate control in suitable steps, of voltage, and shape of restriking-voltage wave, the vulnerability curve of a breaker can be plotted from its performance.

ACKNOWLEDGMENTS

The authors would like to record their indebtedness and thanks to the following for assistance in connection with this paper:—

To the British Thomson-Houston Co. for permission to publish details of the instrument developed, and to their colleagues, Mr. H. E. Cox and Mr. D. J. Mynall, for criticisms, advice, and help.

To the Switchgear Testing Co., Ltd., for permission to publish results of performance of the instrument when installed in their Test Station, and to Mr. V. A. Brown of that company for making special tests and furnishing information thereon.

APPENDIX I

CURRENT-SURGE GENERATOR DESIGN

Factors to be considered are:—

(a) The effect of load impedance on the current-wave shape.
(b) The desired amplitude of restriking voltages.
(c) The effect of resistance losses in the mutual inductance on the current-wave shape.
(d) The frequency and amplitude of oscillations within primary and secondary coils of the mutual inductance under operating (virtually short-circuit) conditions, as affecting the upper limit of frequency response.
(e) The effect of eddy currents upon the frequency-amplitude characteristic.

Of these factors, (a), (b), and (c), will be considered analytically, and factors (d) and (e) qualitatively.

Factor "a."

On closing T, we have, from Fig. 3(a),

$$L_1 p i_1 - M p i_2 \simeq E^*$$

and

$$L_2 p i_2 - M p i_1 \simeq - i_2 Z$$

and the restriking voltage is given by

$$e = i_2 Z \simeq EK\sqrt{\frac{L_2}{L_1}} \cdot \frac{Z}{L_2(1 - K^2)p + Z} \quad . \quad (1)$$

where the flux coupling factor K is defined by $M = K\sqrt{(L_1 L_2)}$ and the winding resistances R_1 and R_2 are neglected. Now by writing

$$F \simeq \frac{Z}{L_2(1 - K^2)p} \quad . \quad . \quad . \quad . \quad (2)$$

we have

$$e \simeq \frac{EK}{L_2(1 - K^2)}\sqrt{\frac{L_2}{L_1}} \cdot \frac{Z}{p}(1 - F + F^2 - \ldots) . \quad (3)$$

or

$$i_2 \simeq \frac{K}{L_2(1 - K^2)}\sqrt{\frac{L_2}{L_1}} \cdot \frac{E}{p}(1 - F + F^2 - \ldots) . \quad (4)$$

Since the ideal surge current is of form E/p, where E is the voltage applied at the crest of an alternating voltage wave, it will be seen from equation (4) that distortion of the current surge is less than F, and F is to be interpreted as that fraction of the effective secondary impedance (when T is closed) which is offered by the external load Z. It remains now to assess the maximum effect of F in giving rise to errors in surge form.

For a given generator, the error fraction F is proportional to the instantaneous value of restriking voltage,

* The sign $\simeq$ is here used to denote equivalence between $f(p)$ and $h(t)$.

so that for a system impedance of known 50-cycle value it is sufficient to consider a form of load which can give rise to the maximum value of restriking voltage. Such a form is obtained from the simple shunt resonant circuit L, C (Fig. 3b) for which

$$Z \simeq \frac{1}{C} \cdot \frac{p}{p^2 + 1/LC}$$

whence
$$F \simeq \frac{1}{CL_2(1 - K^2)(p^2 + 1/LC)}$$

Solving this equation, the maximum value of F corresponding to a load inductance L becomes

$$F_m = \frac{2L}{L_2(1 - K^2)} \quad . \quad . \quad . \quad . \quad (5)$$

Factor "b."

By neglecting the error F, and assuming a resonant load L, C, for Z, we may write down for the maximum value of the restriking voltage e_m in terms of the generator and system inductances

$$e_m = \frac{2E \,.\, K \,.\, L}{(1 - K^2)\sqrt{(L_1 L_2)}} \quad . \quad . \quad . \quad . \quad (6)$$

Equations (5) and (6) can be rewritten in the following

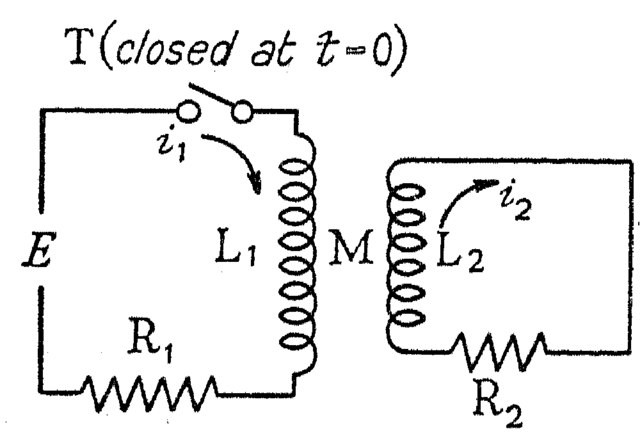


Fig. 8.—Elementary diagram of surge generator, including effective series resistance.

forms, which are more convenient for the design of a surge generator:—

$$K = \frac{e_m}{EF_m}\sqrt{\frac{L_1}{L_2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$L_2 = \frac{2L}{F_m} + \left[\frac{e_m}{E}\right]^2 \frac{L_1}{F_m^2} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and
$$F_m = \frac{1 - K^2}{K^2}\frac{L_1}{2L} \cdot \left[\frac{e_m}{E}\right]^2 \quad . \quad . \quad . \quad (9)$$

Factor "c."

Turning now to the influence upon the surge form of series winding resistance (Fig. 8), and neglecting the effect of Z, it can be shown that the secondary current consequent upon applying unit function voltage* E, is given by:—

$$i_2 = EA\left[t - (a + b)\frac{t^2}{2!} + \frac{a^3 - b^3}{a - b}\frac{t^3}{3!} - \ldots\right] \quad (10)$$

where

$$A = \frac{M}{L_1 L_2 - M^2}, \quad a + b = \frac{\phi_1 + \phi_2}{1 - K^2}, \quad ab = \frac{\phi_1 \phi_2}{1 - K^2},$$
$$\phi_1 = R_1/L_1, \quad \text{and} \quad \phi_2 = R_2/L_2$$

* The ideal surge current resulting from unit function applied voltage differs after 500 microseconds by less than 0·5 per cent from the ideal current due to 50-cycle sinusoidal voltage applied at voltage maximum. Thus, in computing errors due to resistance, it is sufficient to regard the applied voltage as unit function throughout the intervals we are considering.

so that the fractional error at time t, due to resistance, can be written

$$\delta < -\frac{\phi_1 + \phi_2}{2(1 - K^2)}t \quad . \quad . \quad . \quad . \quad (11)$$

Factor "d."

We have now to consider the origin and influence of oscillations within the primary and secondary coils of the mutual inductance, under operating conditions. Their origin within L_1 is to be understood as follows:—

On closing T the voltage distribution is first controlled by capacitance, but later by turn linkage, and the change from one regime to the other results in oscillations which

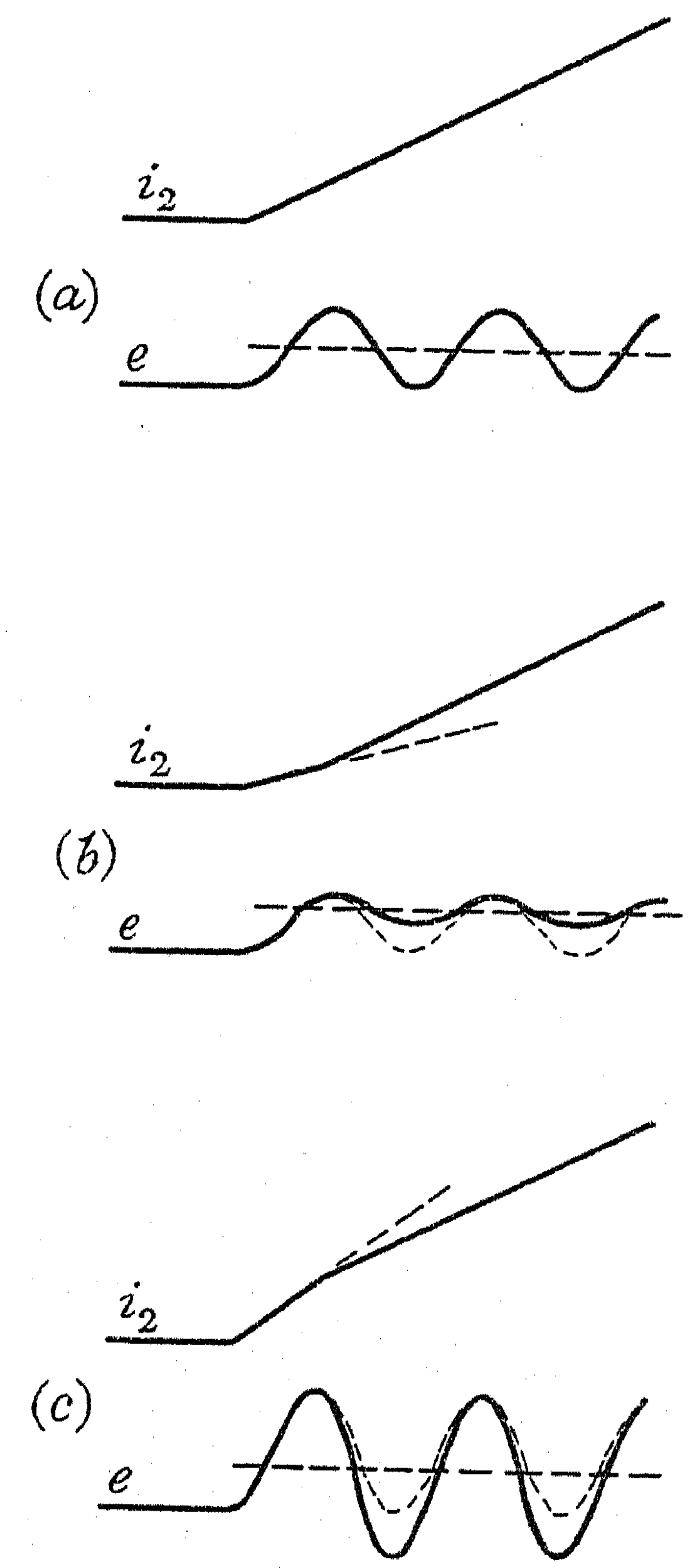


Fig. 9.—Showing, in exaggerated form, the effect upon the circuit LC (Fig. 3b) of discrete changes in slope of the applied surge currents, these changes being intended to represent qualitatively the action of eddy currents.

(a) Undistorted slope.
(b) Slope initially low.
(c) Slope initially high.
The ultimate slope is the same in each case.

extend also to flux linking the secondary coil. By using an iron core in combination with a layer-wound primary coil, the amplitude of these oscillations can be kept small. A similar mechanism exists within the secondary winding, but in this case the condition for no oscillations is that the voltage induced in each secondary turn shall be equal to the voltage which is absorbed in passing the desired surge current through that turn. It has been found that the frequency at which internal oscillations occur becomes the highest frequency at which restriking voltage forms can be generated. Accordingly, care must be taken to ensure that the natural frequency of the short-circuited coils is high. While this presents little

difficulty in the case of the primary winding, the secondary coils have all been wound with as large an insulation space factor as is permitted—having regard to equation (11)—in order to reduce interlayer capacitance and so increase the natural frequency.

Factor "e."

If the circuit of Fig. 3(*b*) is used for the system impedance Z, it can be shown from equation (3), by neglecting F, that the restriking voltage is

$$e = \frac{EKL}{L_2(1 - K^2)}\sqrt{\frac{L_2}{L_1}}(1 - \cos qt)$$

$$\text{or} \qquad e = B(1 - \cos qt) \qquad (12)$$

where $q^2 = 1/(LC)$ and B is independent of C. This result is illustrated in Fig. 9(*a*).

Eddy currents in the neighbourhood of L_1 and L_2 serve to delay the arrival of a constant growth for the flux which links their path. If this flux or a part of it also links the secondary winding, then i_2 will be correspondingly delayed in attaining a uniform growth. Using the superposition principle, Fig. 9(*b*) has been drawn for a surge current of which the slope is initially small but later increases to the same value as in Fig. 9(*a*). By this artifice an exaggerated approximation is made to the case where eddy currents delay the generated surge current. The corresponding restriking-voltage form depends upon the point at which the change in current slope occurs, but the general effect is to reduce the amplitude of oscillations while retaining the level about which oscillations occur. Somewhat unexpectedly, an opposite effect was noticed in that the restriking voltage showed a tendency at certain frequencies to develop negative minima and increased maxima.

This effect is also due to eddy currents, but they are here associated with flux which does not link the secondary winding. Thus, if the total primary flux has a time shape fixed by the applied voltage, and part of it is distorted by eddy currents, it is reasonable to suppose that the remainder will also be distorted but in the opposite sense. The action is shown approximately by Fig. 9(*c*), where it is seen that the general effect is to increase the amplitude of oscillations while retaining the level at which they occur.

A measure of correction is possible by providing artificial eddy-current paths so disposed as to compensate for the original eddy currents. This method of correction is used and has proved successful in the present instrument.

DISCUSSION BEFORE THE INSTITUTION, 17TH DECEMBER, 1936, ON THE PAPERS BY PROF. THORNTON (SEE PAGE 457) AND MESSRS. TRENCHAM AND WILKINSON (SEE PAGE 460).

Mr. L. Satchwell: In connection with the control of heat it is important to find means for switching electrical circuits from the exceedingly small movements obtainable by direct thermal expansion of metals. The switching means have to be such that long contact life will be possible, both in respect to pitting of contacts and as regards oxidation.

The opening of contacts by the direct expansion of a thermally-sensitive device has always seemed to be impracticable, because the contacts are moved apart at a speed which is very slow indeed. Fig. A gives a portion of an oscillogram showing the result of opening a pair of contacts directly from such expansion movement, the current in the circuit being 15 amps. at 250 volts (r.m.s.). It will be seen that the circuit is interrupted and remade a number of times and at each interruption an arc is formed, which is extinguished at the following zero point only to restrike when the voltage rises sufficiently, since, during this period and also for some seconds following, the contacts have not been moved sufficiently far apart to avoid breakdown of the gap. It is quite usual for such intermittent arcing to last over a few hundred cycles, and after some months of working the arcing has a considerable damaging effect on the contacts, apart from being the source of serious radio interference. The speed of movement of the contacts in this case was of the order of 0·005 in. per minute.

An alternative means of circuit-breaking is illustrated by the average tumbler switch or rotary-type switch such as is used to-day on electric cookers. Although these well-known types of switches interrupt small circuits quite satisfactorily, the large arc which is obtained would be detrimental to the working of a sensitive instrument such as the thermostat. Fig. B shows four oscillograms representing the breaking of a circuit by a rotary snap-action switch, the current in the circuit being 15 amps. at 250 volts (r.m.s.). It will be seen that while the circuit is interrupted satisfactorily at the first zero, following the opening of the contacts, the current is considerably reduced by the resistance of the long arc obtained, the whole of the energy represented by this reduction being released in between the switch contacts. The speed of movement of the contacts in this case is approximately 1 000 ft. per min., and since the contacts move through a distance of approximately 1 in. an arc of this length is frequently obtained. Apart from the difficulty of dealing with such long arcs, there is also the great difficulty of obtaining such large movements from changes in temperature of only 2 or 3 deg. F. on the thermally-sensitive element of a thermostat.

In the micro-gap switch it is only necessary to have an opening distance of approximately 0·005 in. to interrupt satisfactorily circuits of the same capacity as I have previously mentioned, and since the contact-opening distance is so small there is almost a complete absence of any destructive arc. Fig. C shows six oscillograms taken on a micro-gap switch, the current in the circuit being 15 amps. at 250 volts (r.m.s.), unity power factor. The arrow on each oscillogram indicates the point where the contacts commence to open, and it will be seen that in each case the circuit is interrupted at the next zero of current. Further, where the contact-opening point comes before the peak of the last half-cycle, it will be seen that this peak is slightly smaller in amplitude than

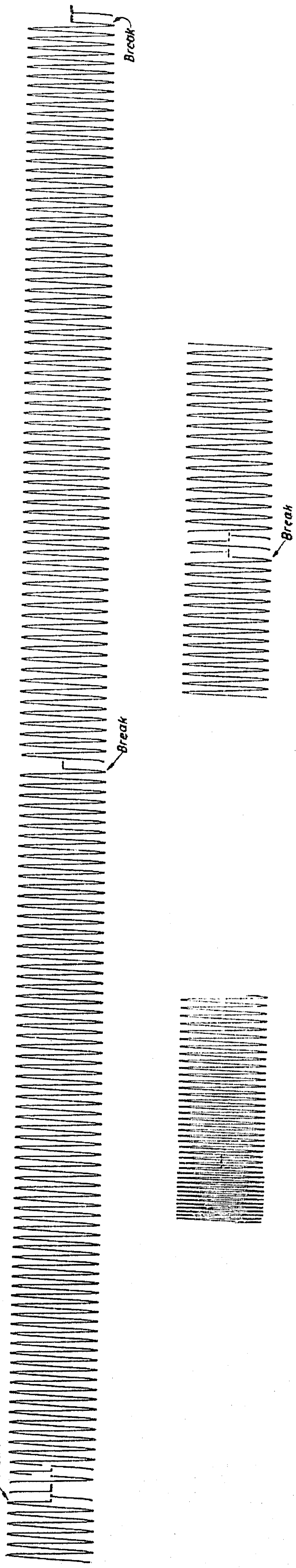


Fig. A

the preceding peaks, and it will be clear that the energy liberated in the arc by this very slight reduction is of a very small order. It may be interesting to compare the speed of the micro-gap switch with the speed of the other two forms of switching I have mentioned: the speed of opening of the contacts in the micro-gap switch is approximately 5 ft. per min.

Concerning the use of the micro-gap switch on inductive circuits, I should like to say that many thousands of examples of the micro-gap switch are working on inductive circuits without the least sign of trouble, and, further, oscillograph records taken on circuits carrying 15 amps. with a power factor of 0·2 show that the circuit is finally interrupted at the end of the half-cycle in which the contacts open.

Mr. C. H. Flurscheim: The instrument described by Messrs. Trencham and Wilkinson has already proved itself to be of value to designing engineers in analysing the effects of restriking voltages on circuit breakers, and arc leakage currents and cut-off currents may be calculated by simple deduction from its readings. It will also be of value in enabling a quantitative analysis to

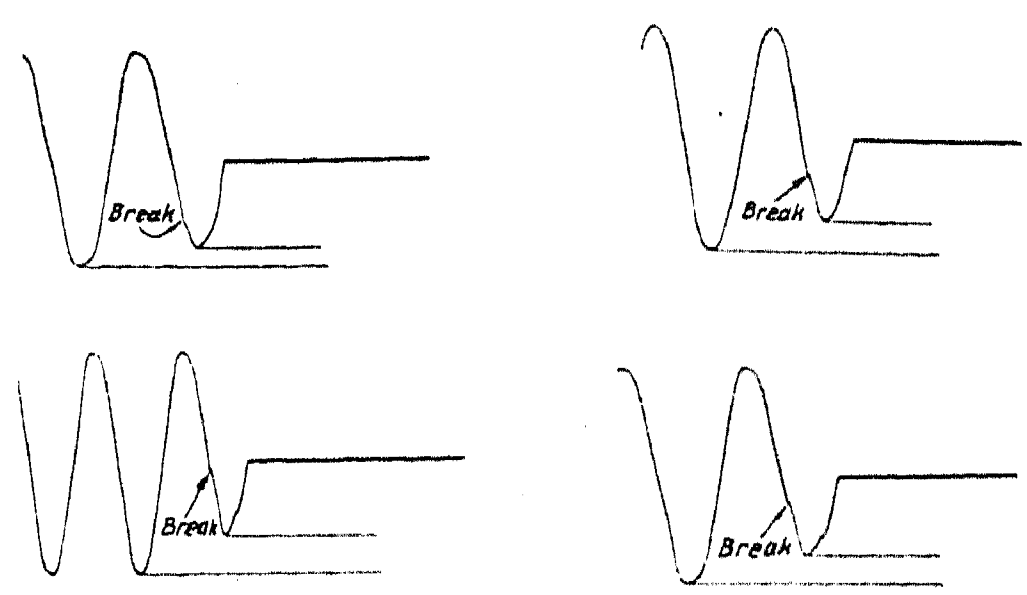


Fig. B

be made of the restriking rates on supply systems. This has not so far been practicable, because supply engineers resent having short-circuits applied to their systems, as has been necessary in the past when cathode-ray methods have been used.

I think it is a pity, however, that the authors do not contribute any new ideas or experimental work on what the effect of restriking voltages is on circuit breakers, although this subject would appear to be covered by the title of the paper. I would ask them whether they can give any such information in their reply.

We in Manchester have so far conducted only a few such tests, which, while they do not purport to be a complete research programme, may nevertheless be of interest. We tested a plain circuit breaker with constant short-circuit current of the order of 10 000 amps. and with varying restriking waye-form, obtained by modification of the circuit constants either by an alteration in generator excitation or by the addition of capacitance or damping resistance. The first test was made at 11 kV with a restriking rate, measured by the conventional tangential method, of 400 volts per microsecond, and with a maximum peak of 15 000 volts on the first high-frequency oscillation. The wave-form was similar to that shown at D in the authors' Fig. 7. This test was then repeated with a damped circuit obtained by apply-

ing resistance across the circuit breaker, and the wave-form was modified to that of the middle curve at F. Although the generator excitation had not been altered, the high-frequency peak was reduced from 15 000 to 9 000 volts and the restriking voltage from 400 volts per microsecond to about 25 volts per microsecond. As the result of this modification, the tank pressure was reduced to one-third of its previous value. A third test was then made at 6·6-kV excitation on an undamped circuit having a characteristic wave-form such as that shown at D, with a similar high-frequency peak to that of the second test, i.e. 9 000 volts, and with a rate of rise of 300 volts per microsecond. There was no appreciable difference in performance in the two instances. For this particular breaker, therefore, it is clear that an 11-kV circuit can be made equivalent in severity to a normal one of 6·6 kV if damping is applied.

Both these conditions were obtained in the test plant, but both of them could also occur under different conditions on a system; thus it appears that this design was fairly insensitive to rate of rise, and was very sensitive to change in peak voltage. We also observed that some plain-break designs perform better on a circuit of the wave-form shown at E, having a rate of rise of the order of 1 200 volts per microsecond (i.e. with generator and a reactor close up to the circuit breaker, but with a peak of perhaps only 75 per cent of the theoretical doubling), than on a circuit of the wave-form shown at D, having a rate of rise of about 400 volts per microsecond but a peak of 96 per cent of the theoretical doubling—the sole difference in the two sets of tests being the addition of capacitance. This is contrary to what is generally accepted, and we attribute it to the fact that the severity of the test was increased to a greater extent by the increase in peak voltage than it was reduced owing to the reduction in the rate of rise of restriking voltage.

Other observers have noticed that with plain-break circuit breakers a very considerable reduction in severity is produced by reduction in the rate of rise, and an analysis of published results has already appeared in the *Journal*.* This only serves to emphasize the inconsistency of plain-break circuit breakers. Forced-blast or "oil impulse" circuit breakers have been shown to be practically insensitive to peak voltages over very wide ranges; for instance, on a 3-in. arc with sufficient applied oil pressure and efficient control they may be insensitive up to 250 000 (peak) volts without change of arc duration, and yet they have also been shown to be directly responsive to rate of rise above certain critical values. As might be expected, the contacts of the self-generated arc control types, such as the cross-jet, appear to be a compromise between these two and are influenced to some extent by changes both in rate of rise and in peak.

It is therefore evident that a great deal of investigation remains to be done both on systems and on circuit breakers before any definite conclusions can be arrived at which will permit of the use of less severe test-plant circuits than are now employed in this country. While in some instances, with some breakers and in certain positions on systems, less severe testing conditions would undoubtedly be justified, it is not yet possible to predict which instances these are, and ultimately in this respect the restriking indicator may well be of actual financial value to the supply industry.

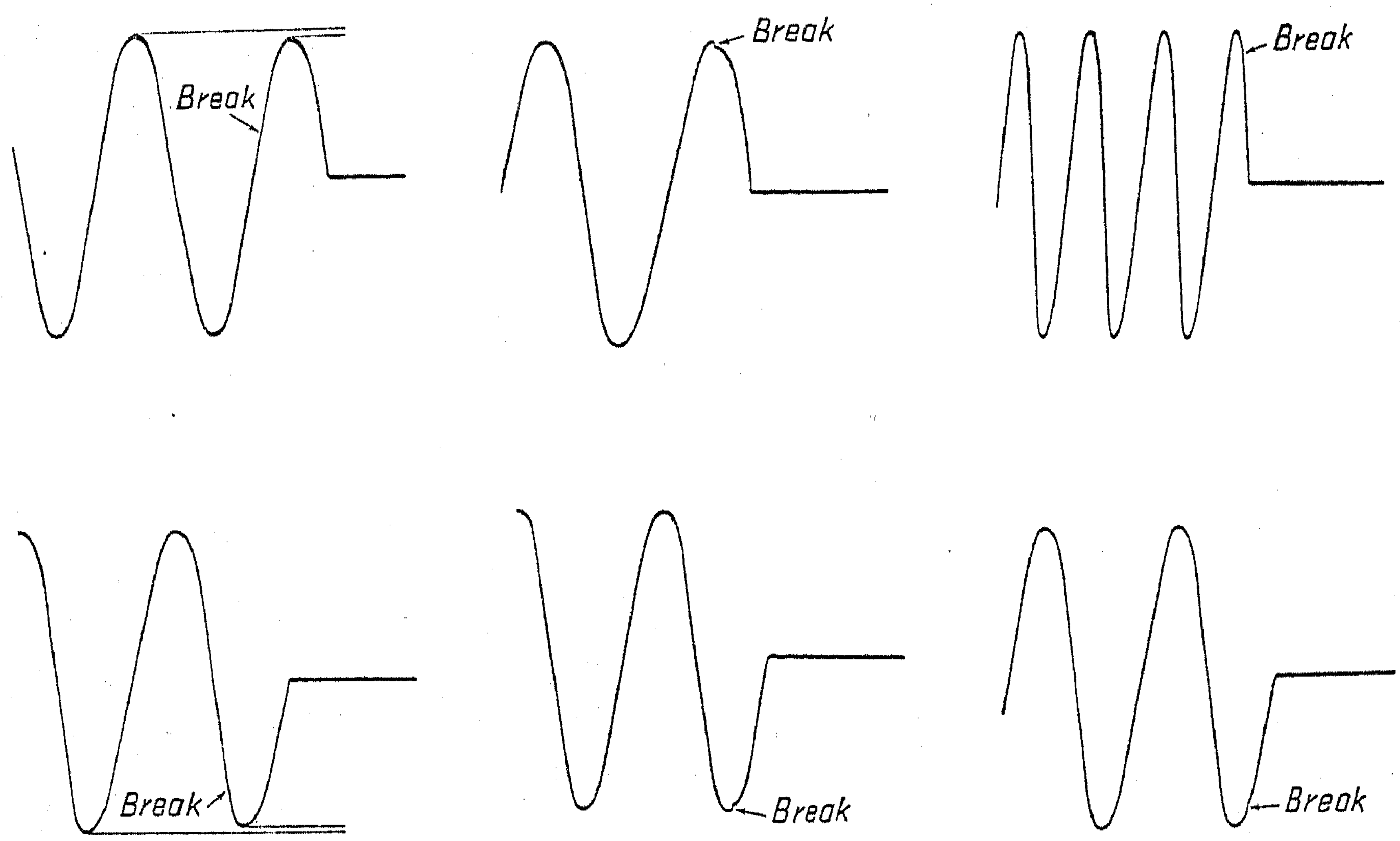


Fig. C

I should like to add one remark on the paper by Prof. Thornton, namely that some years ago we made tests on a single-phase 110-volt micro-gap switch with a gap of the order of 30 mils, and we found the breaker did not fail whatever current was put through it, up to the maximum limit available of over 5 000 amperes. The limit of capacity appears to be reached only when contact welding occurs, and high-power station circuit breakers comprising in effect a large number of micro-gap switches in series have been constructed in America.

Mr. L. Gosland: I am particularly fortunate in being able to speak from experience of the restriking-voltage indicator, because, during the latter part of this

* C. H. Flurscheim: *Journal I.E.E.*, 1935, vol. 76, p. 323.

summer, the Electrical Research Association was able to obtain the loan of the instrument for a few days to try out its possibilities for research work: and I should like to take this opportunity of acknowledging on behalf of the Association its indebtedness to the Switchgear Testing Co., Ltd., for the loan of the instrument.

There are two questions which are of major interest in connection with a study of the field of usefulness of the restriking-voltage indicator (R.V.I.): Firstly, to find to what extent transients of restriking voltage differ in wave-shape when generated in circuits that are identical except for the condition of magnetization of any iron traversed by magnetic fields linking the current flowing in the circuit. (This is of special interest, as transients of restriking voltage occur when iron in generators, transformers, iron-cored chokes, etc., is already in a state of magnetization which is changing, whilst the R.V.I. in its present form can only be applied to circuits which are dead.) Secondly, to find whether the current surge input to the system provided by the surge-generator portion of the apparatus is in fact approximately linear over the time in which we are interested—any failure in this respect would, of course, result in some distortion of the indicated transient. (It is fairly safe to assume that the voltage-amplifier and indicating portions of the R.V.I. depict accurately whatever voltage transient is applied to the recording terminals.)

There is a further question, in connection with the general accuracy of the R.V.I. as a recorder of transients: that of the error likely to arise when using the instrument on frequencies outside the recommended range of operation.

To answer the above questions, tests were made with a number of circuit arrangements, the circuit being made dead in each test with the R.V.I., and alive and carrying fault current in each corresponding test with the cathode-ray oscillograph (C.R.O.), the breaker being open in the first case and being opened to clear the fault current in the second case. In order to ensure that the records obtained with the C.R.O. were not seriously affected by the characteristics of the arc gap, a switch was used which had very little arc voltage, and negligible transient post-arc conductivity, both of which are features to be avoided if the true restriking-voltage characteristic transient of the circuit is to be obtained. To answer the first question, the circuits for some of the pairs of tests were specially laid out to show up the effects of iron on the shape of the transients of restriking voltage as recorded by the R.V.I. and the C.R.O. respectively. To provide answers to the second and further question respectively, tests were made (*a*) on a system for which, for a linear applied current, the voltage transient should have been linear over a known time from the instant of application; and (*b*) on circuits containing oscillatory

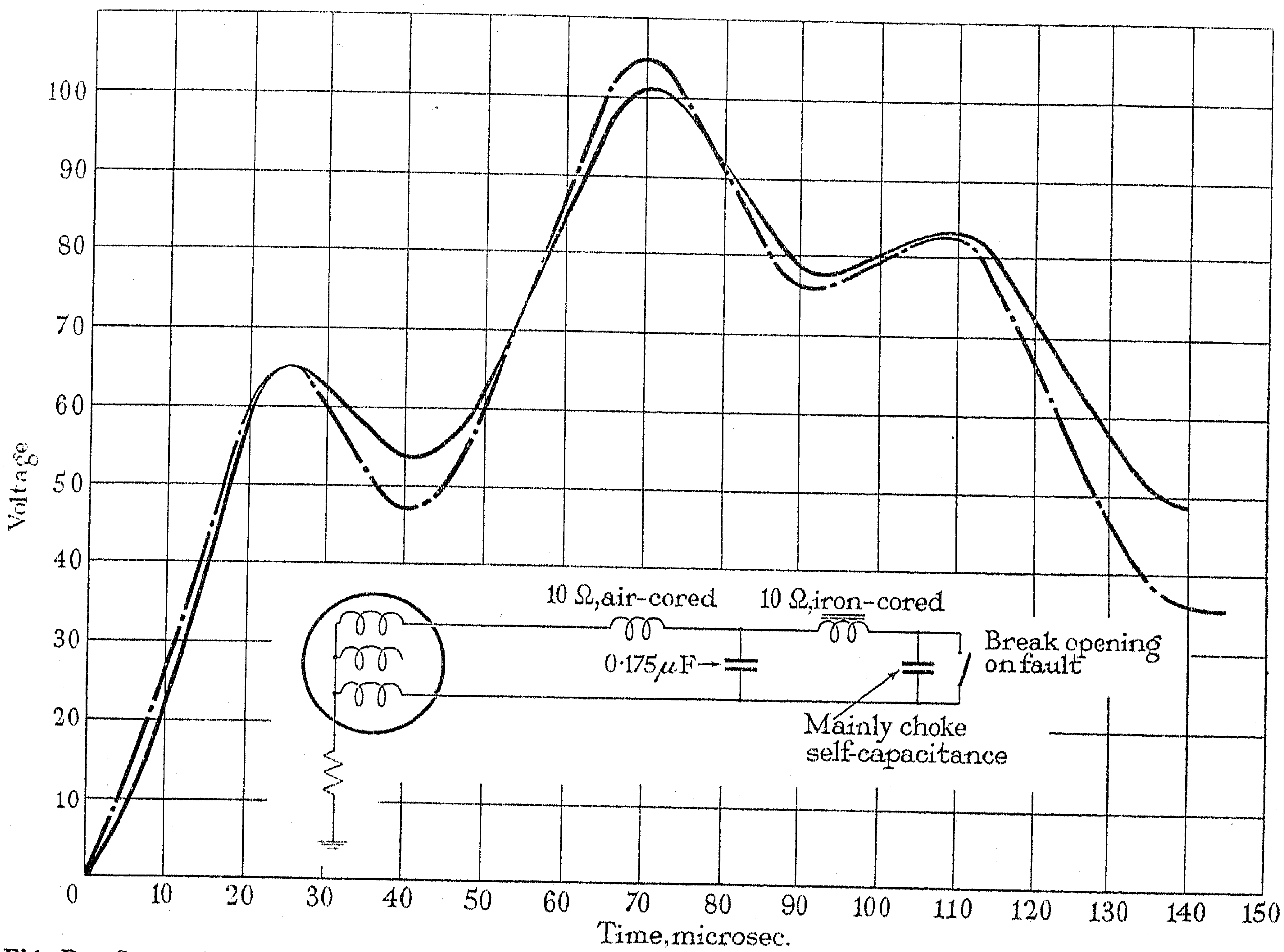


Fig. D.—Comparison of R.V.I. and C.R.O. records (C.R.O. corrected for arc voltage) taken on circuit with air- and iron-cored reactance.

——— C.R.O. record (R.V.I. range 4) (test at 3 300 volts, 160 amps.).
—·— R.V.I. record (machine stopped, with no excitation).

components having frequencies well above the advocated upper limit.

The results of some of the tests are given in a series of diagrams, each of which shows the C.R.O. and the R.V.I. records for one circuit drawn to the same time scale. The vertical scales are entirely arbitrary, since no attempt has as yet been made to utilize the method of calibration described by the authors. Further, in no case except the first (Fig. D), has the C.R.O. record been corrected for what arc voltage existed: for instance, in with the iron-cored reactance was about 3 times that associated with the air-cored reactance. The C.R.O. record has in this case been corrected for the effects of arc voltage, so that in theory, if the restriking-voltage indication and the correction for arc voltage were both quite perfect and the difference in states of the iron had no effect, the two records should coincide. The agreement is, in fact, quite good.

The second pair of records (Fig. E) was taken on the same generator dead short-circuited across two phases with the capacitance of about 180 ft. of 3-core 6 600-volt cable

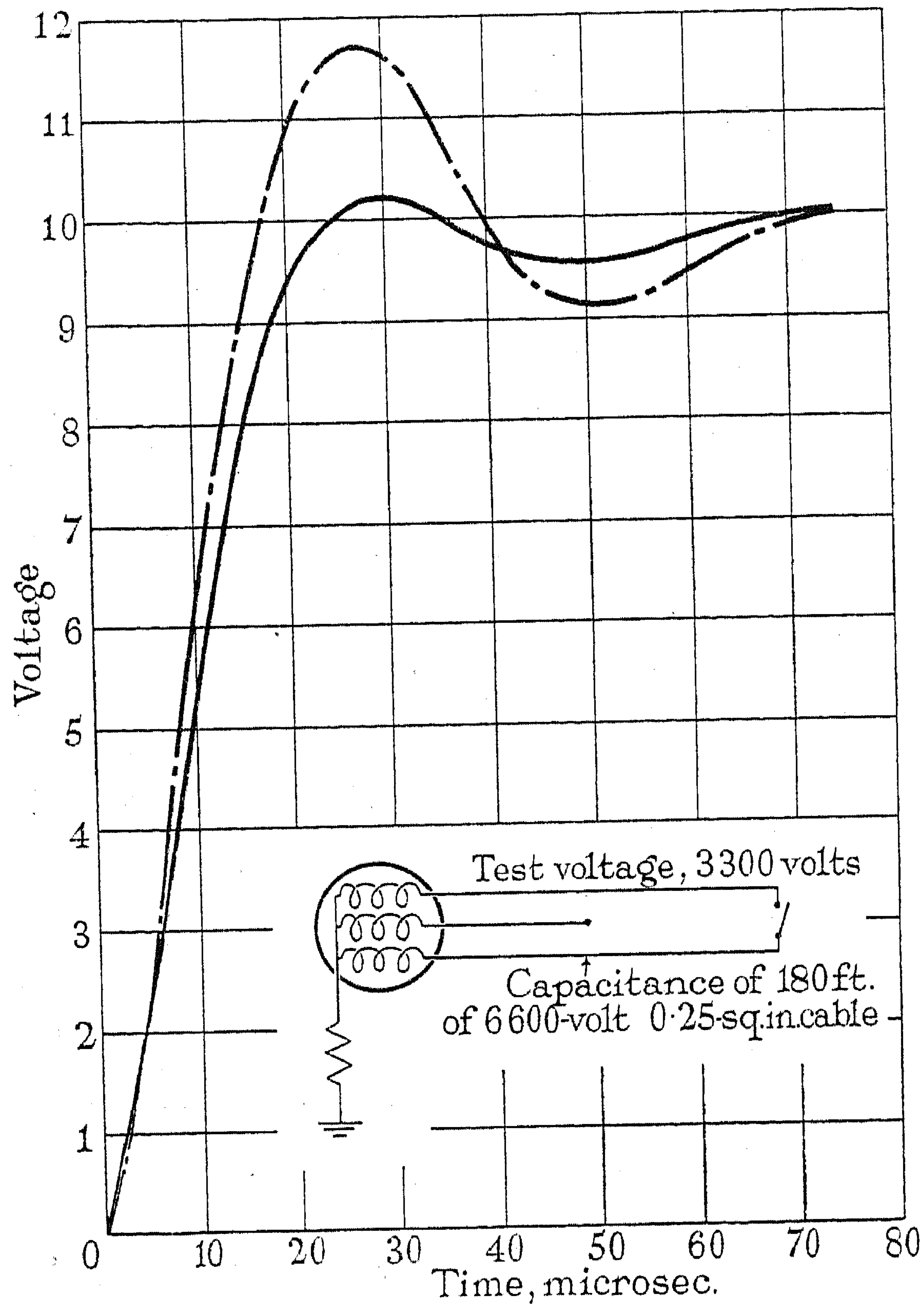


Fig. E.—C.R.O. and R.V.I. records on identical circuits including short-circuited generator, showing difference in degree of damping indicated by C.R.O. and R.V.I. on generator alone. (C.R.O. not corrected for arc voltage.) (R.V.I. range 2.)
——— C.R.O. record (test at 3 300 V, 3 600 A).
—·— R.V.I. record (machine stopped, with no excitation).

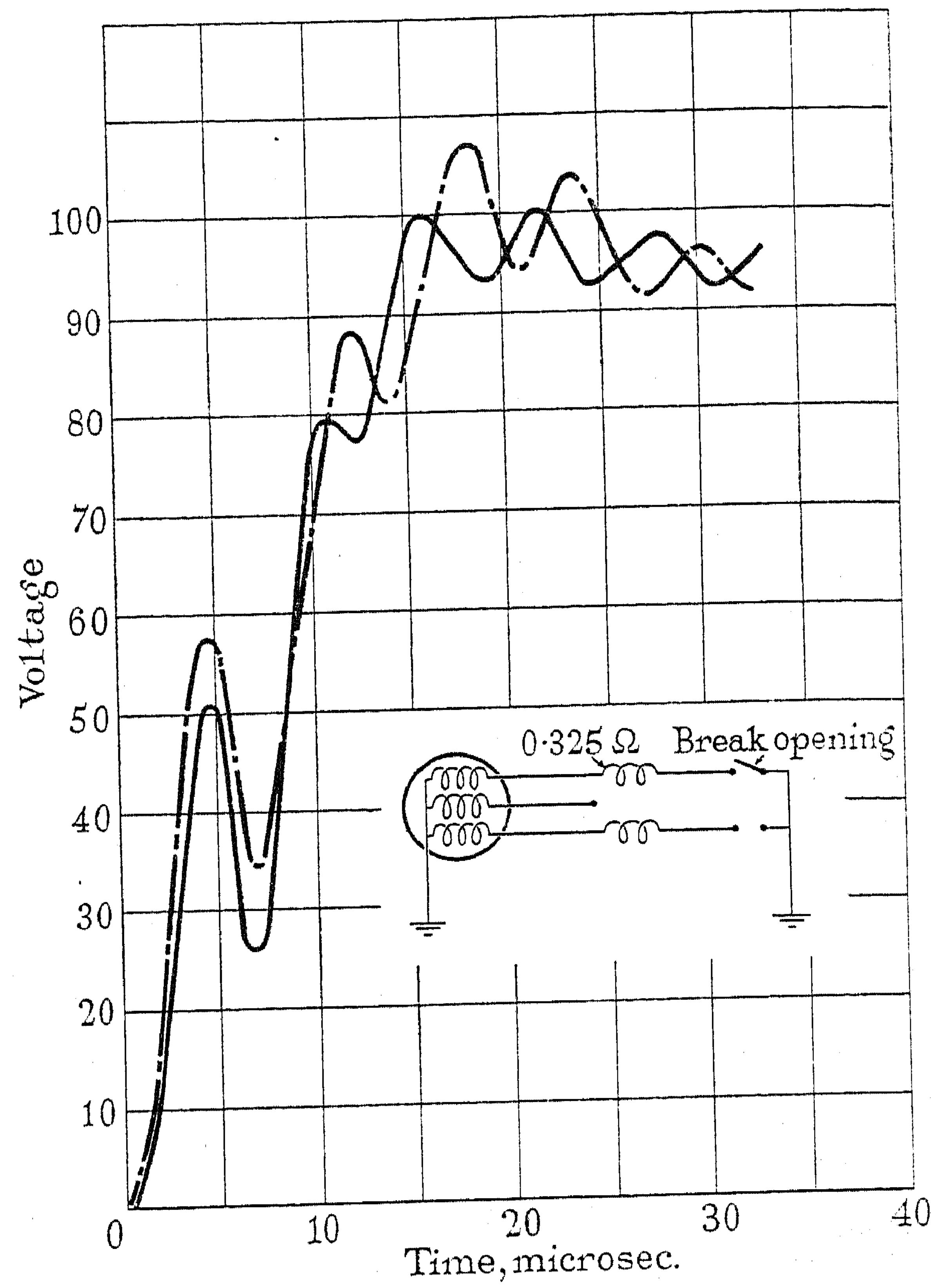


Fig. F.—C.R.O. and R.V.I. records at interruption of 2nd phase to clear of a phase-phase-earth short-circuit. (Very compact generator-reactor circuit.) (C.R.O. not corrected for arc voltage.) (R.V.I. range 2.)
——— C.R.O. record (test at 3 300 V, 3 000 A).
—·— R.V.I. record (machine stopped, with no excitation).

Fig. G the distance between the peak arc voltage and the recovery voltage was taken as 100 per cent. Before going into details it should be mentioned that the result of the comparison indicates quite good agreements between the R.V.I. and C.R.O. records.

The first pair of records (Fig. D) was taken on a circuit designed to indicate whether any differences might be anticipated between the transients recorded on the R.V.I. and the C.R.O. due to the presence of iron-cored reactance in a circuit, at various degrees of magnetization. A circuit was made up consisting of a 6 600-volt 10 000-kVA generator, an air-cored reactance, and an iron-cored reactance in series; and capacitance was added in such a way that the frequency associated at its terminals. The R.V.I. record was taken with no current in the field circuit of the stationary machine, while the C.R.O. record was taken with the running machine excited to 3 300 volts and with the breaker clearing 3 600 amperes at contact separation. The R.V.I. record clearly shows that the transient produced with the unexcited stationary generator was one with considerably less damping than that shown by the C.R.O. record of the transient in the system containing the partially-excited generator under running conditions; this is apparently connected with the same saturation effects as lead to the variation of frequency with field current mentioned by the authors.

The third pair of records (Fig. F) was taken with

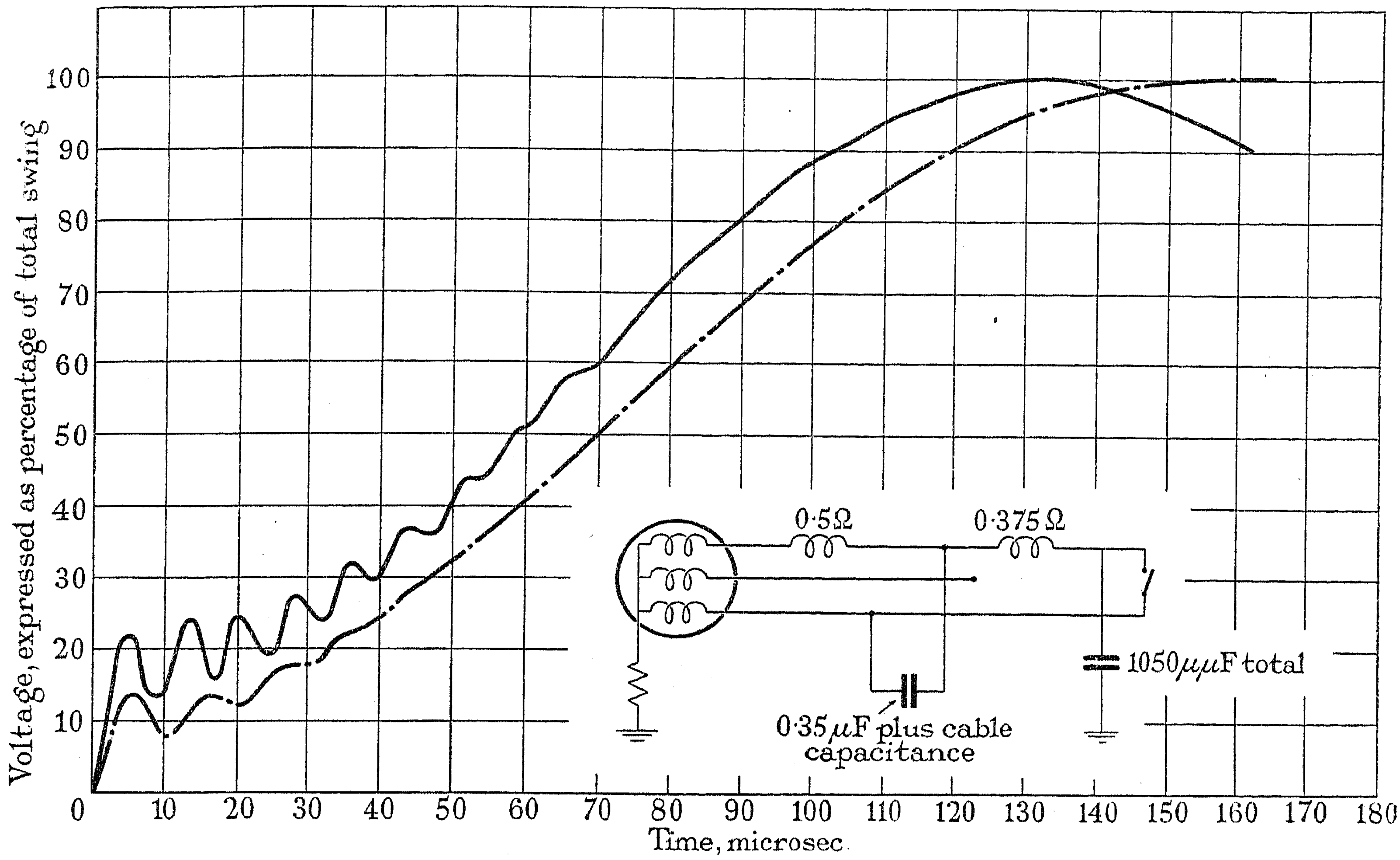


Fig. G.—C.R.O. and R.V.I. records on generator-reactor circuit giving very high and very low frequencies (C.R.O. not corrected for arc voltage.) (R.V.I. range 3.)

——— C.R.O. record (test at 6 600 volts, 2 800 amps.). —·— R.V.I. record (machine stopped, with no excitation).

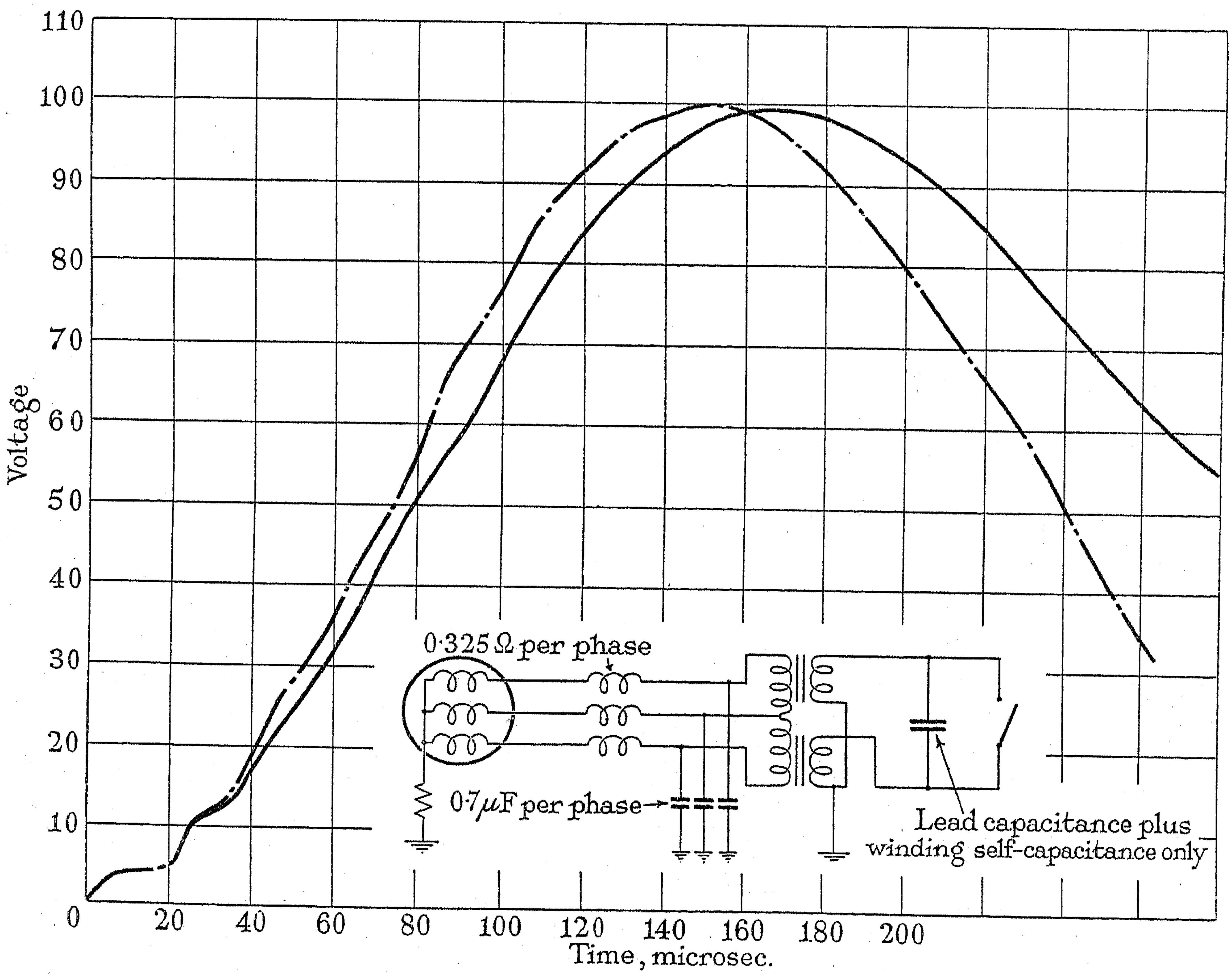


Fig. H.—C.R.O. and R.V.I. records on same generator-reactor-transformer circuit, with transformer frequency isolated. (C.R.O. not corrected for arc voltage.) (R.V.I. range 4.)

——— C.R.O. record (test at 11 000 V, 600 A; generator voltage 3 300). —·— R.V.I. record (machine stopped, with no excitation).

circuit layout corresponding to the opening of the second phase to clear of a phase-phase-earth short-circuit, a reactor being placed close up to the generator terminals and with all the capacitances on the system quite small. The frequency associated with the reactor oscillations is 160 kc, but the R.V.I. record, on the dead circuit with stationary machine, appears to show this component as being of rather lower frequency (150 kc). Further, as in the second pair of records mentioned above, the component due to the stationary unexcited generator is shown, by the R.V.I., as slightly less damped than that on the live circuit clearing the fault on the running with smaller amplitude, compared with the value which the C.R.O. shows it to have, and which also agrees with calculations. It should be noted, however, that this high-frequency component is also beyond the frequency range within which the errors in the R.V.I. are expected to be small.

The next two pairs of records (Figs. H and J) were taken on a circuit comprising generator, reactors, and transformers, with capacitance added to keep the two frequencies distinct. Here again the agreement is quite good between dead and live circuit conditions over the important part of the record.

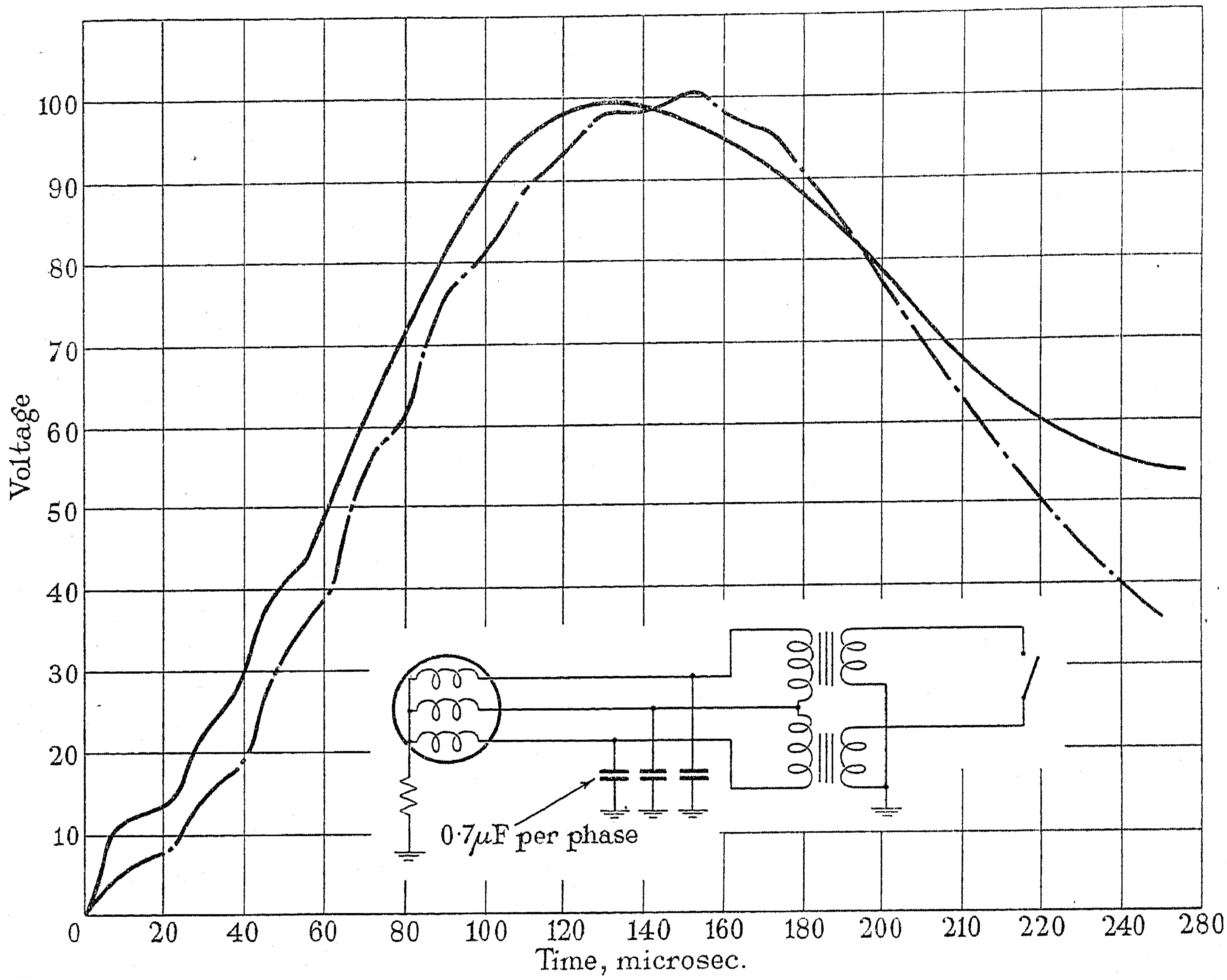


Fig. J.—Comparison of R.V.I. and C.R.O. records on same generator-transformer circuit, with transformer frequency isolated. (C.R.O. not corrected for arc voltage.) (R.V.I. range 4.)

——— C.R.O. record (test at 11 000 V, 700 A; generator voltage 3 300).
—·— R.V.I. record (machine stopped, with no excitation).

machine excited to 3 300 volts, as shown on the C.R.O. It should be noted that the frequency of the high-frequency component on this record is above the limits within which the authors indicate (see Fig. 4) that the error should be small on the R.V.I.

The fourth pair of records (Fig. G) was taken on a somewhat similar circuit, but with a very large amount of capacitance added to keep the generator frequency distinct from the reactor frequency. Here again, the R.V.I. shows the high-frequency component as of slightly lower frequency than that indicated by the C.R.O. Furthermore, the R.V.I. shows the high-frequency component of the circuit as rather more highly damped, and

The pair of records shown in Fig. K was taken of the transients between phases at the end of a cable 11 miles long. The C.R.O. record was taken at the interruption of a 5 000-amp. 33-kV fault between phases, and in consequence the terminal condition at the far end of the cable was that there was, so to speak, a generating station between phases. It was of course not possible to repeat this condition when the R.V.I. was applied to the cable, as the station could not be made dead; and the generating station was in this case replaced by a short-circuit. The two records should, however, be of the same form (without reference to amplitude) over the time taken by a wave-front to traverse the cable from

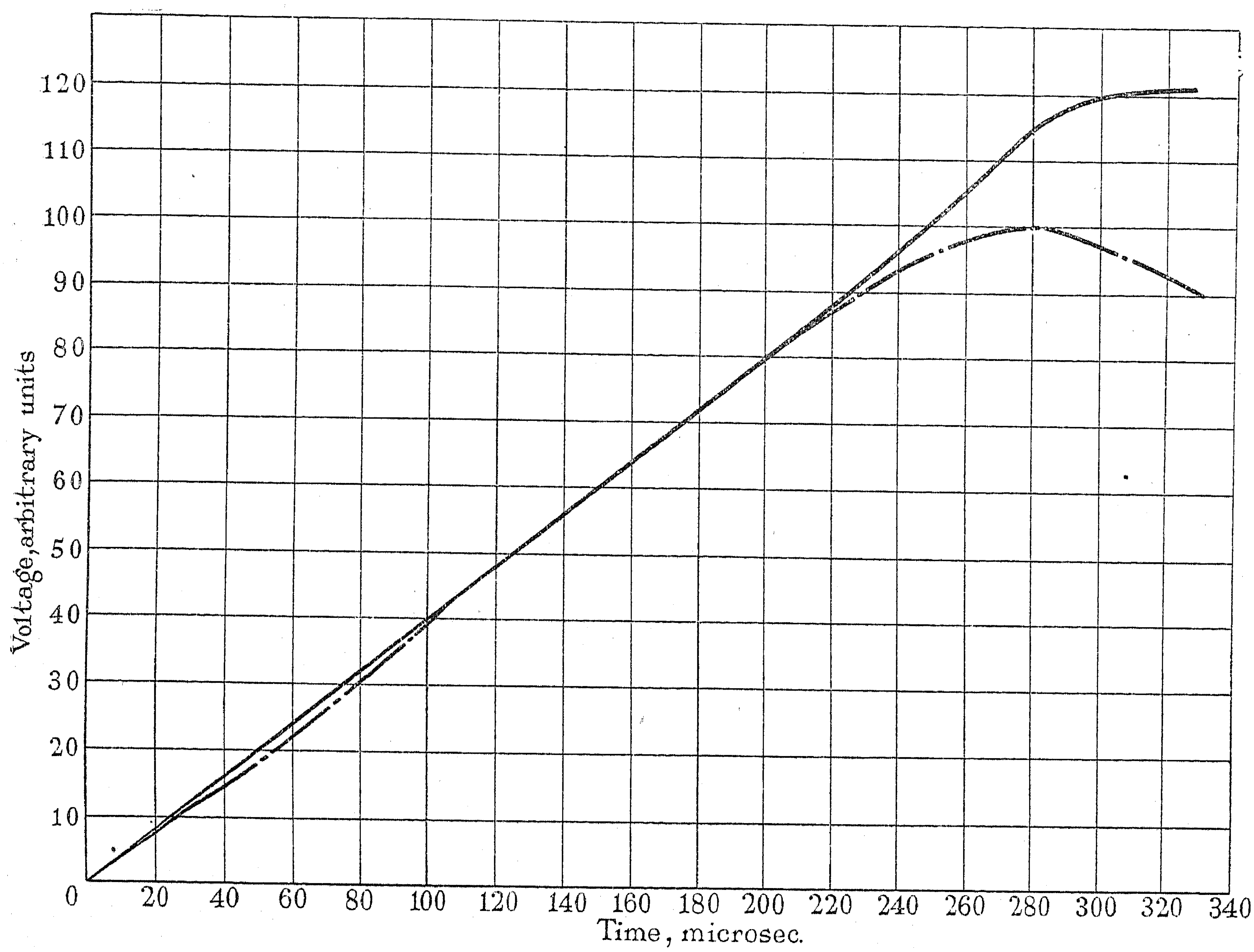


Fig. K.—C.R.O. and R.V.I. records taken on the same system, except that the C.R.O. record was taken with generating station at far end of cable, R.V.I. record with short-circuit at far end of cable.

——— C.R.O. record (test at interruption of 5 000 A at 33 000 V between phases).
—·— R.V.I. record.

end to end and return; and various considerations led us to put this time at about 280 microseconds. The agreement between the two records is in fact quite good over the first 200 microseconds or so; and we may conclude that, over this time, the current output of the surge-generator portion of the R.V.I. equipment is of the desired linear form. The divergence of the two traces, after 200 microseconds, might appear to indicate some departure from linearity, but the authors, whom we have consulted on this point, consider that a more probable cause is some error in the timing apparatus of the R.V.I. as we used it on that occasion, when it had to be put into service immediately on arrival at the test site after travelling some distance by road.

With reference to the effect of field current on the degree of damping exhibited by the R.V.I. when applied to generating plant, it is perhaps of interest to show another set of records (Fig. L); these are the oscillograms obtained by applying the R.V.I. to a stationary generator with approximately 0, 12, and 40 per cent of the full field current in the field. There is a marked effect both on the total impedance and on the degree of damping exhibited.

To summarize, it can be said that the records the R.V.I. gave on dead circuits, when compared with C.R.O. records taken on the same circuits, and assumed to be correct delineations of the surges occurring under live fault conditions, show quite good agreement. Certain differences in frequency and amplitude may be due to the effect of differences in the magnetization of the iron

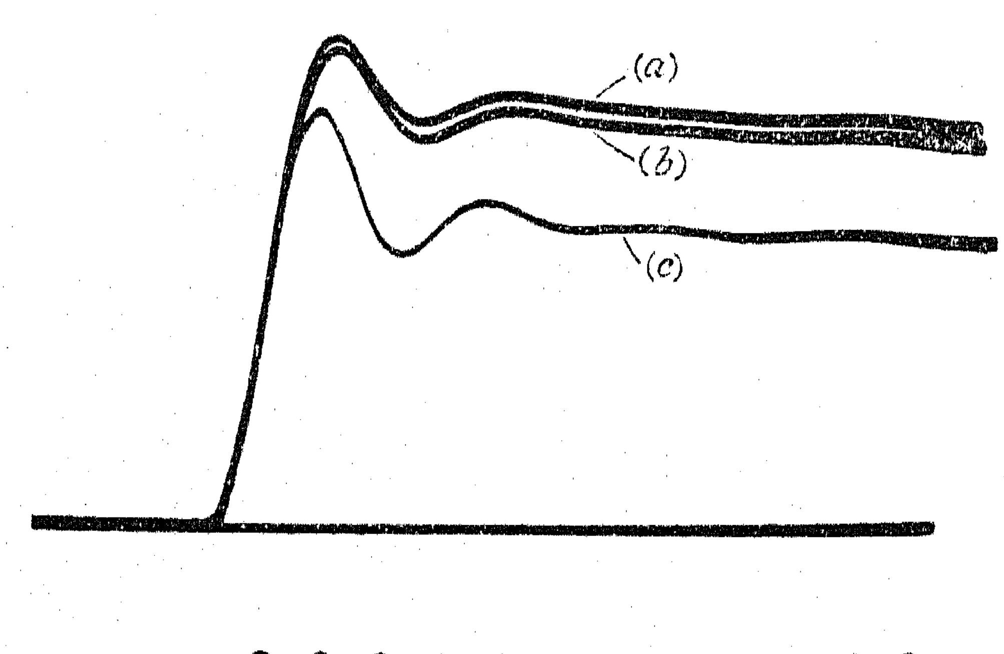


Fig. L.—R.V.I. record taken between phases at terminals of stationary 10 000-kW 6 600-volt generator with (*a*) 0, (*b*) 12 per cent, (*c*) 40 per cent, full excitation current in field. Timing wave 99 kc.

associated with the circuits. Also, even when frequency components exist which are somewhat outside the ranges indicated, the errors arising do not appear excessive. The authors indicate that, to obtain an accurate delinea-

tion of the restriking-voltage transient, the system must be complete, i.e. one cannot apply the instrument to an isolated portion of a system and get the full story about the restriking-voltage transient due to the system as a whole. This requirement indicates the limitation of the instrument in its application to power systems. In a test plant it is of course a simple matter to make the complete system dead so that an R.V.I. record may be taken under any desired circuit conditions: but this is not so in a power system. The chance of extensive parts of a power system being made dead so that such records may be taken appears very remote: and records taken at any point on an isolated portion of a system may require quite a considerable amount of correction before they represent conditions at the same point when the whole system is connected up in its operating condition. I make this point not to deprecate the general utility of the instrument, but rather to encourage the authors to develop their design so that the instrument may be applied to a live circuit.

Mr. V. A. Brown: I should like to refer to the case mentioned at the top of the second column on page 465 of the paper by Messrs. Trencham and Wilkinson. Taking the restriking-voltage wave with (*a*) no excitation, rotor and stator poles coincident; (*b*) rotor and stator poles coincident, excitation at virtual saturation; (*c*) rotor and stator poles displaced 90°, with the machine saturated; as shown by the authors, the change in frequency is not very great (the actual values are 44·8 kc., 47·1 kc., and 49·8 kc. respectively).

Referring to the conditions on power systems, there is no doubt that in many cases the restriking voltage builds up in a non-oscillatory manner. Record F in Fig. 7 shows that resistance was added in shunt with the circuit in order to calibrate the 50-cycle recovery-voltage value. On the circuit to which record F corresponds, the short-circuit MVA available is 288. The resistance used to damp out the wave would correspond to a 3-phase load on a power system of about 2 MVA at 11 kV. If in that case there had been a 2-MVA shunt load on the side of the breaker remote from the fault, the restriking voltage would have been non-oscillatory.

Up to now it has been the practice to draw a tangent from the zero-voltage line to the front of the wave and to take the slope of the tangent as being the rate of rise of restriking voltage, on the basis that if the break insulation across the contacts is built up at a rate greater than the slope of this tangent, the breaker will interrupt the short-circuit. When we come to measure the rate of rise on an exponential wave, since the wave-front is concave to the zero axis a tangent can be drawn only at the zero point, and similarly with many other irregular wave forms of restriking voltage. A simpler method, and one which can be applied in all cases, is to take the rate of rise of restriking voltage as the average rate of rise from the zero line to the peak of the wave. I put forward the suggestion that for recording purposes we should measure the peak to which the restriking voltage rises and divide by the time taken to reach that peak. Where there are many crests on the wave-front, the wave will have to be recorded as a number of rates of rise and peak values. Furthermore, I should like to suggest that a restriking-voltage wave which, for example, rises at 2 000 volts per microsecond to 26 kV, should be recorded as a 2 000/26 restriking-voltage wave.

Mr. C. J. O. Garrard: The recent discussions in connection with the new circuit-breaker specification of the International Electrotechnical Commission, and in connection with the revision of B.S.S. No. 116, make it clear that there are still important gaps in our knowledge of circuit-breaker theory; the development of the restriking-voltage indicator described by Messrs. Trencham and Wilkinson, which gives us a powerful new means of research, is therefore an important event, as it will be of great assistance in clearing up the points on which doubt exists. It is curious that although we can and do make satisfactory circuit breakers, it is difficult to lay down an entirely satisfactory specification for testing them and to define rigidly the severity of a particular test.

A great amount of money has been spent during recent years on building and running testing stations in this country; the results which have been obtained, however, are so far somewhat disappointing from the point of view of the emergence of a co-ordinated body of theoretical knowledge. It would be greatly to the advantage of both manufacturers and users of switchgear if closer collaboration could be obtained between the owners of testing stations and those engaged in research, in making public the results obtained, and also in carrying out agreed programmes of co-operative research. The problems to be solved are so difficult and the necessary work is so extensive and elaborate that it seems almost hopeless for any one manufacturer to carry it through to a successful conclusion.

One of the most urgent questions awaiting solution at the moment is that of the relative severity of a given duty cycle performed in a testing station and on a supply network. As the authors say, it seems that in this country, at any rate, the severity of test circuits is generally greater than the severity of supply networks. Several Continental writers have advanced the opposite opinion, however, and their arguments and test results are such that one cannot take a hasty decision on the question. The only way to settle it conclusively will be to carry out comparative tests, obviously a somewhat expensive matter and hardly one to be undertaken by an individual manufacturer.

The authors apparently consider that they will be able to compare severity conditions on different testing networks and in different testing stations by means of the restriking-voltage indicator. At present, however, I cannot see much justification for assuming that any particular shape of curve as given by this instrument indicates more or less severe conditions as regards a circuit breaker installed at the point where the tests are made. It has not yet been demonstrated that an experiment made with very small power, such as is used for the restriking-voltage indicator, can allow accurate conclusions to be drawn concerning operation under service conditions, which involve powers of many thousands of kilowatts.

The restriking-voltage indicator will be useful in the investigation of the effect of protective reactances on circuit-breaker duty. Practical experience shows that the presence of a reactor electrically near a circuit breaker, in spite of reducing the fault current, may in

certain cases increase the severity of the duty on the breaker; and in consequence it is generally considered good practice not to install reactors or transformers electrically close to circuit breakers, but to interpose a certain length of cable or busbar. A complete investigation of the matter would, however, be of great value.

I should like a further elucidation of the suggested definition of rate of rise of restriking voltage given on page 460.

Turning to Fig. 7, what is the time scale for the records shown? What is meant by "Maximum amplitude reached, expressed as a percentage of the theoretical maximum possible"? Why are the figures of maximum amplitude and time omitted in the case of record C? What is the maximum value on record B? Presumably it occurs at the second peak, but one would have thought that the first peak was at least as important.

Have the authors any figures with regard to the effect on the curves of restriking voltage of the capacitance-to-core of the secondary of the injecting transformer? This capacitance must be appreciable, and, as it seems that the addition of a very small capacitance on the circuit near the indicator produces quite considerable differences in the shape of the restriking-voltage curve, there appears to be some danger of the capacitance between the secondary and the core having an influence on the results.

Have the authors found that disturbances on the supply system affect the operation of the instrument? In Birmingham we have made some experiments and have experienced trouble due to such surges. I understand that in one case where this instrument is in use there is a special generator to supply it.

Mr. J. K. Brown: It would be interesting to know the voltage-recovery characteristics of the micro-gap switch, as it is possible that even at higher voltages and lower power factors the performance will be satisfactory. Perhaps Prof. Thornton will eventually be able to extend his theoretical work and develop higher-voltage circuit breakers of the same type. I do not think there is sufficient evidence to show that the best place at which to break a non-inductive circuit is not at a current zero, but in the quarter-period before a zero pause. In oscillogram (*a*) the record is not clear, and it is possible that the contacts have separated immediately after the zero pause. Investigations with a cathode-ray oscillograph would give a much more accurate picture of the arcing voltage.

Messrs. Trencham and Wilkinson have introduced a very novel means of investigating the restriking-voltage characteristics of circuits, but have given little evidence of its importance with regard to circuit-breaker performance. For several years investigations have been in progress to establish the effect of the rate of rise of the recovery voltage on the operation of circuit breakers. Slepian has published curves showing the rate at which the electric strength is restored after the zero pause of current. These results are not yet applicable to all types of circuit breakers.

In 1932 some data* were contributed on the effect of the natural frequency of oscillation on the performance of a plain-break oil circuit-breaker. At that time the conclusion was that above a definite frequency (of the order of 3 000 cycles per sec.) the curve reached a saturation point beyond which the circuit breaker was not influenced otherwise than by the recovery voltage; that is, by the peak of the voltage-transient oscillation. Since then many similar tests have been carried out on circuit breakers, and I think that view still stands not only with regard to the plain-break but also with regard to many other types of oil circuit-breakers. Perhaps it is just as well that this is the case, because at the time when that view was developed it was thought that a testing plant was very much more severe than a network. In this country there are several power stations with outputs of the general order of 200 000 kW supplied by machines running at 3 000 r.p.m. A dead short-circuit on the busbars of such a station would result in a very high rate of rise. These high-speed machines are now of much smaller physical dimensions than the low-speed machines; this means that the electrostatic capacitance has been reduced, the short-circuit reactance is lower, and as a result the natural frequency of oscillation is considerably higher. Thus the conditions on the busbars of a generating station are probably not very much less severe in extreme cases than in a testing plant. The interconnection of generating stations by overhead lines and cables reduces the severity very considerably, so that it is only in very exceptional cases that the conditions in a network are as severe as in a testing plant.

If the instrument described by Messrs. Trencham and Wilkinson is to be made a useful tool for the purpose of analysing networks they must try to get it to work with the system under test alive. I do not consider that this is impossible. Experience with a method not quite the same as the one the authors have used shows that with the system alive it is quite possible to imitate the conditions of the second phase to clear of a short-circuit, and under such conditions the natural frequency has been measured on the network under voltage. I feel, however, that the real value of this instrument to the supply undertakings is that it enables them to measure one or more parts of a network in order to determine the characteristics, so that with a certain type of layout it will be possible to calculate the resulting frequencies on a circuit breaker for certain conditions. In order to do this we have to analyse such curves as are given in Fig. 7, and to find out from them the frequencies and amplitudes of oscillation.

I find the greatest difficulty in analysing these curves when I do not know the frequencies. Where the restriking-voltage curve is composed of two frequencies which are not widely different, e.g. 5 000 and 7 000 cycles per sec., it means that we have to analyse not the lower frequency (say 5 000) but to assume, according to Fourier, a modulation frequency of 2 000 and analyse a number of half-cycles. The modulation frequency has zero amplitude, and we can determine the frequencies and amplitudes assuming that the damping coefficient of each of the oscillations is the same. If the damping coefficients of the oscillations are widely different, as is generally the case in practice, we shall find at the end of one period of the modulation frequency that one of the oscillations has totally disappeared. I should be glad if the authors would give their views on this subject.

* *Journal I.E.E.*, 1932, vol. 71, p. 729.

One of the most difficult problems to solve is that of the natural frequency of a transmission line. Most of the lines, in spite of the fact that they can be made dead, run either near or parallel to some other lines which are under voltage; and, even if the 50-cycle voltage wave has been completely eliminated, the harmonics, though they are a very small percentage of the 50-cycle wave, amount to a considerable percentage of the voltage which is used to operate the surge indicator.

Mr. J. O. Knowles: The restriking-voltage indicator described by Messrs. Trencham and Wilkinson paves the way to the investigation of resistance conditions in a circuit breaker. I should like the authors to say to what extent, knowing all the conditions of the circuit, it is possible to predetermine the oscillograms (made by means of the ordinary Duddell oscillograph) which will be produced in a test under new circuit conditions on a circuit breaker which has already been tested under other circuit conditions.

Dr. W. B. Whitney: Prof. Thornton touches on the interesting question of what happens if the gap of a micro-gap switch is opened as the current passes through zero, and in this connection it would be helpful if we could have a little more information with regard to oscillogram (*a*), which seems to provide the only evidence in the paper for the conclusion that the arc will persist if the gap is formed at a current zero. On examining the oscillogram in question, it will be noticed that there is a horizontal line (presumably representing the arc voltage) just to the right of the arrow and below the zero line, and at the end of the half-cycle it seems to tail off in a curve into the general zero line. It seems as if this last trailing-off portion is not the voltage record but part of the trace made by the current oscillograph unit, and it looks as though the vibrator was not following the current quite accurately (i.e. the current was probably slightly leading the actual record); the actual passage of the current through zero value is probably slightly to the right of the arrow. It is a matter of considerable interest to know whether an arc could be prevented from forming if one could somehow separate contacts to a sufficient distance as the current is passing through zero, and it would be helpful if the author could give more information on his experiments on this point.

Turning to the paper by Messrs. Trencham and Wilkinson, I am in agreement with the statement, at the foot of the first column on page 460, regarding the difficulty inherent in the suggested method of expressing the rate of rise referred to there. In the second column on the same page there is a reference to the importance of carrying out tests on different types of circuit breakers on a circuit with particular characteristics, and also to the lack of data regarding restriking voltages on power systems. My colleagues and I have already done some work on the first-mentioned problem and it may also be of interest to mention that a considerable amount of co-operative work has been carried out during the past year, as a result of which we have obtained a number of cathode-ray records of transients of restriking voltage under live fault conditions on two large supply systems in this country. The results of the field work are now in course of preparation for publication.

In conclusion, I should like to say that the instrument described by the authors, though it can at present only be used where apparatus or portions of systems can be made dead, is a very welcome addition to the tools available for use in circuit-breaker research, and it is hoped to purchase one of these instruments in the near future for the E.R.A.

Mr. F. E. J. Ockenden: Dealing first with Prof. Thornton's paper, nothing has yet been said of the danger of the contacts becoming permanently closed due to building-up on one side or the other. I should like to know whether there has been any experience in that direction. The current, being alternating, is as likely to break in one direction as the other, but a very small margin would cause a contact to build-up and completely close as fine a gap as 0·005 in.

The paper by Messrs. Trencham and Wilkinson has two aspects, the first relating to circuit breakers, on which a great deal has been said, and the second relating to the restriking-voltage indicator instrument, on which very little has been said. Fig. 1 may appear fearsome at first, but on analysis we realize that it is really made up of three diagrams. The lower section shows a push-pull amplifier, whose only important characteristic is that its response should be regular over a wide range of frequencies. The middle diagram represents a cathode-ray tube circuit of ordinary construction, except for the cunning way in which the time-switch coil has been linked up with the thyratron, the firing of which initiates the current surge. I should like to know whether difficulties arose in obtaining consistent traces on the oscillograph screen due to variations of a few microseconds in the time of firing of the thyratron.

There are a number of factors controlling the point at which the thyratron fires. The first is the exact position of the peak on the transformer: is it the experience of the authors that the position of that peak is constant over a long sequence of operations within the very few microseconds necessary to get accurate scanning? Secondly, it depends on the voltage applied to the anode of the thyratron, for the thyratron fires when the balance of grid bias is just not sufficient to prevent the anode current passing. If the anode voltage varies during the period in which the readings are taken, the firing of the thyratron will be shifted by a few microseconds and cause displacement of the image on the cathode-ray screen. Lastly, if the thyratron fires at the peak of the voltage wave the anode current will follow the voltage wave downwards until it reaches 30 volts, after which it will collapse altogether, 30 volts being the minimum voltage which will maintain the discharge. It would appear, therefore, that a full quarter-cycle will not be transmitted by the valve.

Dr. E. H. Rayner: The paper by Prof. Thornton reminds me of the quenched spark-gap of the Telefunken system, which was of the order of 5 mils. Another case which came to my notice a good many years ago occurred on the Brighton line in connection with an overhead section insulator which sometimes failed. It consisted of a number of metal and insulating links of a chain about a yard long. The gaps in this chain between the metal parts were too long, and when they were made shorter the insulator worked satisfactorily.

In India and other countries there is an immense

demand for a.c. fans, which normally have a power factor of about 0·6. Is this low power factor sufficient to put the micro-switch out of action on account of the induction in the circuit? If so, any ordinary small domestic motor might be beyond its capacity. The author speaks of his switch breaking a current of 15 amperes. Does it work well down to zero load? There are certain types of electrical apparatus which will work at a fair load and not at a lower load; certain brands of fuses will not work satisfactorily at a small overload but will work at a much larger overload.

There is a possible application for a switch of this kind in modern prepayment meters. Such switches have to work when the credit runs out, and they have to work fairly often, because there is apparently a prevailing belief in the public mind that if one puts a penny at a time into the meter and waits until it is used up, one gets more electricity than if one puts two pennies in together. Switches in prepayment meters may therefore have a considerable amount of work to do, and the penny switch is much more trying than the shilling switch from the point of view of the meter. It is often necessary to provide the public with a meter which will take pennies, as well as shillings, so that the meter switch which breaks currents up to 15 or 25 amperes is a very important piece of mechanism. This type of switch has given a good deal of trouble in the past. To be a commercial success the meter switch must be able to work at a power factor less than unity.

Mr. J. I. Bernard (*communicated*): I should be greatly indebted if Prof. Thornton could extend his treatment of micro-gap switches to include breaking of d.c. circuits.

Standard thermostats rated at 15 amps. alternating current are commonly quoted as being able to break direct currents up to 0·1 amp. (at voltages up to 250 volts). In addition, it has been found in practice that these switches will break larger direct currents up to 5 or possibly 10 amps., if a condenser of about 2 μF is connected across the switch contacts. An explanation of the action of the switch under these conditions will, I am sure, be appreciated by those who have to use this type of apparatus.

[The authors' replies to this discussion will be found on page 486.]

DISCUSSION BEFORE THE NORTH-WESTERN CENTRE, AT MANCHESTER, 15TH DECEMBER, 1936, ON THE PAPERS BY PROF. THORNTON (SEE PAGE 457) AND MESSRS. TRENCHAM AND WILKINSON (SEE PAGE 460).

Mr. G. L. Woolnough: Prof. Thornton claims that the start of the arc is due to local heating at surface irregularities causing thermionic emission. While this is the most likely explanation, there is also the possibility of the discharge starting owing to auto-electronic emission. The contacts in opening must traverse all distances from 0 to 10^{-2} cm., and the velocity of travel is really quite slow in terms of electron velocity, so that at distances of 10^{-5} cm. the field strength should be ample to pull electrons out of the metal and give the gap the necessary initial ionization. Once the gap was ionized the discharge would rapidly develop into an arc owing to the current density at the electrodes.

In Section (3) of his paper Prof. Thornton claims that the electron energy, and hence the contact pitting, would be reduced with a smaller gap, it being inferred that the applied voltage is constant. Actually one would expect the kinetic energy of the electrons on arrival at the anode to be proportional to the total applied voltage and independent of the distance, so that, apart from the small change in arc voltage, distance should not have much effect on pitting.

The use of magnets to get a quick break has certain disadvantages, and it should be pointed out that various micro-gap switches are known using toggle mechanisms of different types. Also, it seems doubtful whether a quick break is essential for tumbler switches and similar applications so long as the velocity of the moving contact is sufficient to take it past the critical distance in a few cycles.

The great disadvantage of the type of switch described in the paper is that it is limited to substantially non-inductive a.c. circuits and can only break very small direct currents with any reliability It seems a logical development from this to enclose the switching contacts in an evacuated container and thus enable both alternating and direct currents to be broken with very small contact gaps. Such vacuum switches are available which will break their rated loads up to 1 000 volts alternating or direct current with contact gaps of less than 0·001 in. Such switches rated at 30 amps. have been tested up to 100 amps. at 600 volts direct current, and have shown themselves highly suited to d.c. traction work and for general use.

Mr. H. Pearce: While there is plenty of published information as to what happens in a vacuum or in low-pressure discharge chambers, there is comparatively little about the power arc. Can the theoretical section of Prof. Thornton's paper be applied to the long arc, which is the more common application? At first sight it seems unreasonable to speak of an arc in a micro-gap switch as a long arc, but assuming the mean free path given by the author, and his gap width between the electrodes of 5 mils, an electron would have to make about 230 collisions before it had travelled from one electrode to another; so that in some respects conditions must be similar to those in a long arc. In the section "Analysis in Terms of Electrons" the author takes the case of two individual electrons and deduces that they will be in a position of equilibrium with respect to one another as long as their velocity is equal to the velocity of light. I should like to know whether he is of the opinion that, if he takes into account a stream of electrons, the condition of equilibrium will still be so limited that there will be no stability unless the velocity is equal to the velocity of light. I suggest that the conditions may be stable at a much lower velocity, and that in an ordinary power arc the velocity of the electron is appreciably less

than the velocity of light. My picture of an arc is a stream of electrons discharged from one electrode to the other. Each electron is separated from the others by a given distance. The strength of the electric field is an inverse function of the square of the average distance separating two adjacent electrons, which are kept apart and also propelled forward by electrostatic repulsion. The electrons will be approximately equally distributed within a circular cross-section forming the arc space and will be restrained from spreading by the magnetic field induced by the current. It is true that the electron which starts its path from one electrode may not be the same electron as that which reaches the other end of the journey. The original electron may take part in a relay race, and by collision with a molecule or atom take the place of another electron which is ejected to carry on the race; but that does not alter the original conception.

It should be possible for those who have had more experience in these mathematical and physical questions to determine the balance between the energy put into the arc by the electric field and the thermal energy radiated by the arc. The product of the repulsive force, the rate of flow, the number of electrons per unit volume, and the electric charge on each electron, represents a certain amount of energy. That energy is transformed into heat, which has to be dissipated from the cylinder forming the core of the arc in the shape of hot gases and radiated energy. In my opinion the same conditions will apply even for a micro-gap switch, although the length of the arc is very much shorter. As the author's oscillogram (*a*) shows, the current flows on uninterruptedly after contact separation until the next zero point, and the arc voltage slightly increases, so that there appears to be no marked lateral spread of the electrons from the arc stream while the current is flowing. If there were, there would be a corresponding fall in the voltage-drop.

For this reason I am of the opinion that the satisfactory working of the micro-gap switch is due more to the cooling effect of the contacts and the very small total arc energy, than to the sideways repulsion of the electrons, so stressed by the author.

Turning to the paper by Messrs. Trencham and Wilkinson, to get the full benefit of their instrument it must be used on actual systems, and if we are to make the best circuit breaker to suit practical conditions we must find out what the conditions are. I suggest to the authors that in order to make it easier to test on systems we need a still further improvement. At present the test can be made on any system, either in a test plant or on a supply system, so long as the circuit is made dead. What the supply users would like is a method of carrying out the test without the necessity of making the system dead.

Dr. C. Dannatt: Prof. Thornton stresses lateral diffusion of ions as the cause of de-ionization of the gap, but there are other agencies at work contributing to the same end. There is, of course, de-ionization due to recombination of positive and negative ions in the arc stream; but, in the case of the short gap, probably the most important factor is the rapid neutralization of the positive space-charge in the layer of gas at the cathode surface and the recovery of electric strength in that layer. If one measures the breakdown voltage of a spark-gap in air with decreasing length, a limiting breakdown value of 300 volts is obtained, even if the gap length is further reduced. This is due to the fact that if the gap length is less than the mean free path of an electron in the gas, electrons have to be withdrawn from the metal in order to start a spark. This demands a voltage gradient of the order of 10^6 volts per cm., which is evidently reached in air when a p.d. of 300 volts or so is applied to a gap equal in length to the mean free path of an electron in it. Consequently, any arc gap immediately regains an electric strength of 300 volts at current zero, though further recovery is probably much slower. I believe that this initial recovery is a vital factor in the performance of the micro-gap switch, and I should like the author to express his views on this point.

With regard to the paper by Messrs. Trencham and Wilkinson, Mr. Pearce has put his finger upon a point which is of very great importance, because there is still left the difficulty of calculating the restriking voltages on live networks, which cannot be tested by this instrument. One of the authors has suggested that an improvement to their instrument might be forthcoming in that direction, and we should be pleased to learn more of it. At the same time this instrument can be valuable, because it does tell us how various parts of network equipment, like transformers and reactors, react to applied surges. If the authors have had an opportunity of checking the calculated performance of a complex network complete with transformers, by means of this instrument, we shall be glad to learn of the results.

Mr. S. Farrer: From the first sentence in Section (4) of Prof. Thornton's paper it might conceivably be taken that 250 volts r.m.s. is the value which will just fail to break down a gap of 0·005 in. Actually the electric strength of air for small gaps increases to several times the value given by the normal breakdown gradient, i.e. approximately 21 kV per cm. In tests using a spark-gap between ½-in. diameter spheres, illuminated with a 500-watt carbon arc at about 1 ft. distance from the gap, the sparkover voltage for 0·005 in. was approximately 800 volts r.m.s., and for 0·002 in., 500 volts. According to these tests the apparent strength of air for the very short gaps reaches the high values of 64 kV and 100 kV per cm. (r.m.s.) respectively, and it should be noted that these figures refer to gaps where a supply of electrons has been provided from the ultra-violet component of the arc illumination. Without such illumination the apparent strength of the air would be greater by an amount which seems to vary with atmospheric conditions. A value of 250 volts applied to a 0·005-in. gap would give, therefore, a considerable factor of safety against restriking, assuming approximately parallel plates.

Mr. V. A. Brown: With regard to the paper by Messrs. Trencham and Wilkinson, when defining a restriking voltage it is not sufficient to quote the steepness of its wave-front alone; the peak value attained is just as important. In many cases a very high-frequency component, associated with a small peak value, may be of minor importance. On an actual short-circuit test the high-frequency peak may be rendered innocuous by arc voltage which shifts the origin of the restriking-voltage

oscillation across the zero line. The high-frequency peak may thus be reduced or completely eliminated.

A perfect circuit breaker should have negligible arc-gap resistance right up to the final zero of arc current, and immediately after this instant the gap should become non-conducting. So far, the ideal circuit breaker has not been produced, but most modern breakers, in which the arc is under control, show ideal characteristics over limited ranges of current and voltage. In the absence of ideal interrupting performance the conditions in the breaker gap modify the inherent oscillation of the circuit, making it difficult to record the inherent restriking voltage at the end of a short-circuit test.

Before the advent of the restriking-voltage indicator, the inherent oscillation of the circuit could only be roughly estimated by laborious calculation after the oscillatory constants of the circuit had been partly measured and partly estimated. An alternative method was to determine the natural frequencies by resonance tests. Neither of these methods takes care of the damping factor, and hence the final result only gives an estimate of the restriking-voltage wave-front. The

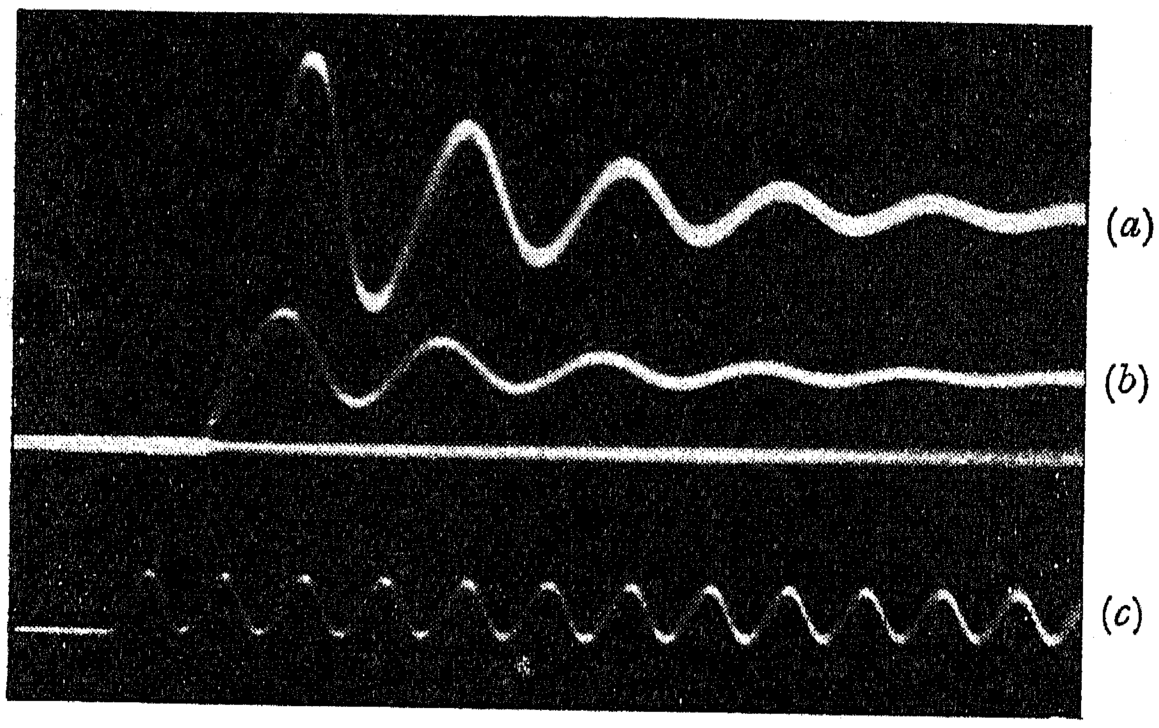


Fig. M

restriking-voltage indicator has made it possible to record the inherent restriking voltage for any circuit combination. In the testing station with which I am associated there are over 1 800 circuit conditions to be calibrated with respect to restriking voltage. Using the indirect methods referred to above, this would be a colossal task. The restriking-voltage indicator eliminates complex circuit calculations and saves an enormous amount of time. As an educational tool, the restriking-voltage indicator would be a useful addition to the electrical laboratory of any college.

Fig. 7A (see Plate) shows the record obtained in a testing station for the inherent restriking voltage on the first phase to be interrupted of a 3-phase generator without current-regulating reactors. The record was taken in the test cell at the end of about 100 ft. of air-insulated test conductors. In this case a faint trace of the oscillatory voltage due to these connections can be seen along the wave-front of the restriking voltage. This higher-frequency component is of no consequence, since the voltage with which it is associated is very small. A record was taken at the generator terminals (see Fig. M). It will be seen that here the higher-frequency component due to the test connections has disappeared [curve (*a*)]. Curve (*b*) shows the oscillation of the neutral point of the generator and illustrates how the restriking-voltage indicator can be used to give a record of the oscillatory voltage at various points along a circuit. Curve (*c*) is a 100-kc. timing wave.

Mr. A. C. Ehrenberg: In the course of my work I have analysed many records taken with the instrument described by Messrs. Trencham and Wilkinson. All these had been obtained on test circuits in connection with short-circuit tests on oil circuit-breakers. For many of these circuits actual 3-phase cathode-ray oscillograms were obtained under short-circuit conditions. It is of great interest to compare these oscillograms with the

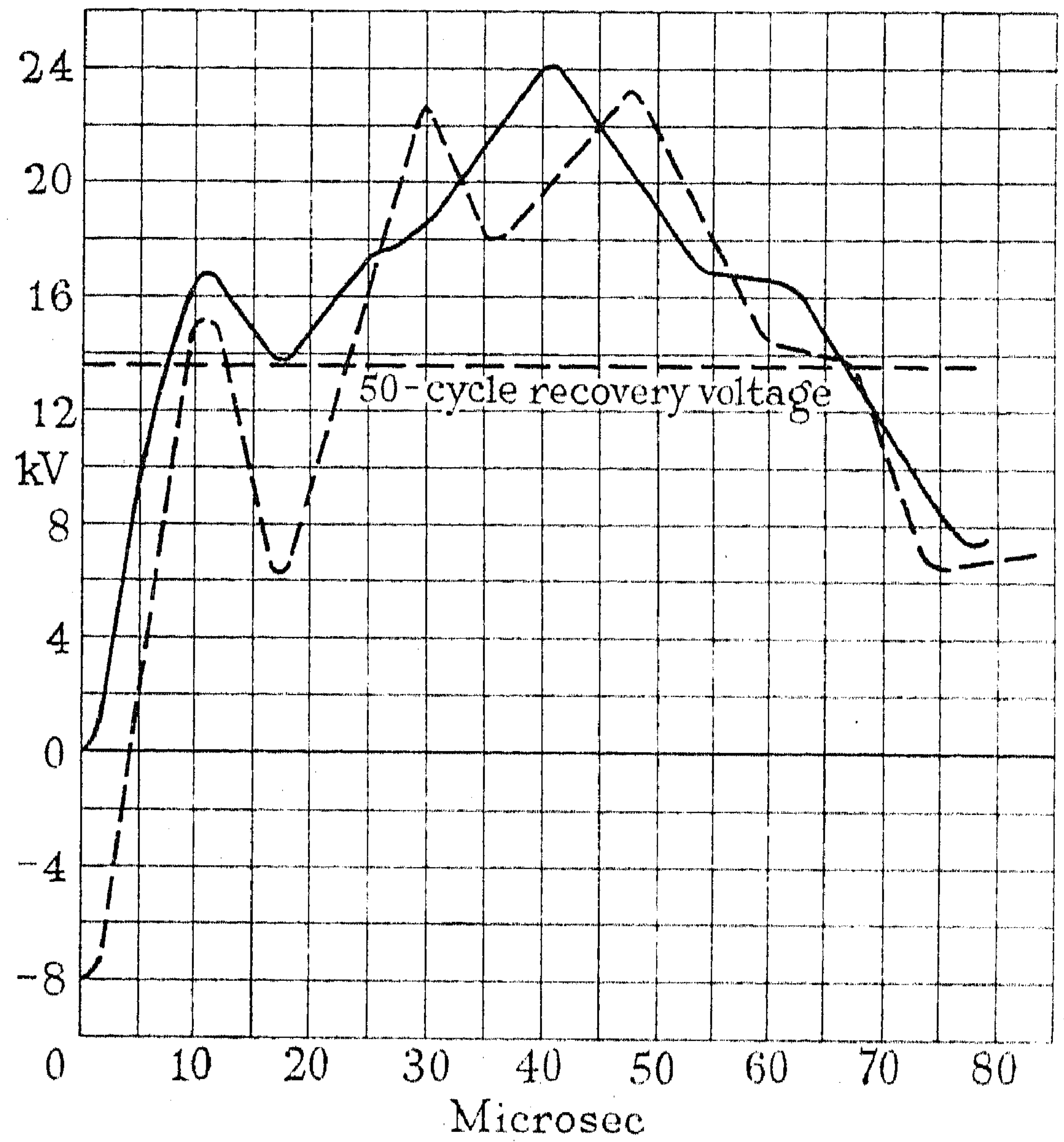


Fig. N

corresponding records obtained with the authors' instrument and to observe the closeness of agreement attained.

My first comparison concerns a circuit with multi-frequency restriking voltage. In Fig. N the full line shows the wave obtained with the authors' instrument, and the dotted line the corresponding cathode-ray oscillogram of the first phase to clear in a 3-phase short-circuit. This is shown to start below the zero line, owing to the presence of arc voltage at the time of arc extinction. It will be observed that the frequencies are very substantially the same. The amplitudes of the higher-frequency oscillation appear less damped on the cathode-ray oscillogram. A close examination of the cathode-ray oscillogram shown in Fig. O reveals that the arc voltages in the other two phases are not equal. This causes an oscillation in the system, which is best illustrated by noting that on the first phase to clear the restriking-voltage oscillations are not damped out into a smooth 50-cycle recovery voltage. This shows that unequal arc voltages in 3-phase short-circuits can increase or decrease the amplitude and also the rate of restriking voltage. The value of the authors' instrument in the calibration of circuits for restriking voltage is enhanced by the un-

avoidable presence of such variables as those outlined above, which are introduced by circuit-breaker operating characteristics. Fig. P gives a similar comparison for a

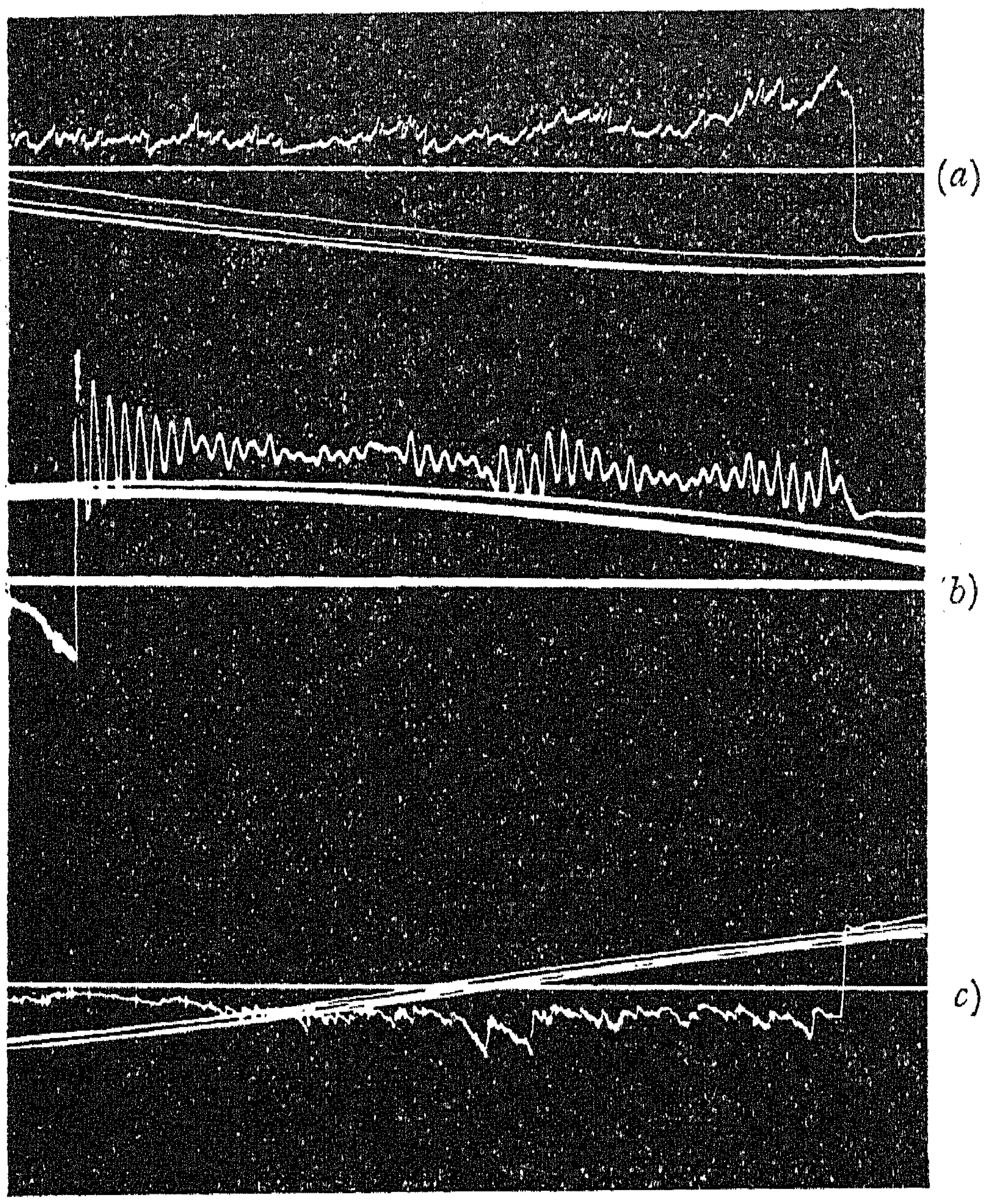


Fig. O

circuit with step-up transformers. The latter can be regarded as an iron-core reactor in the circuit. It is clearly shown that the two records are identical. For these circuits it has been shown that the damping of the

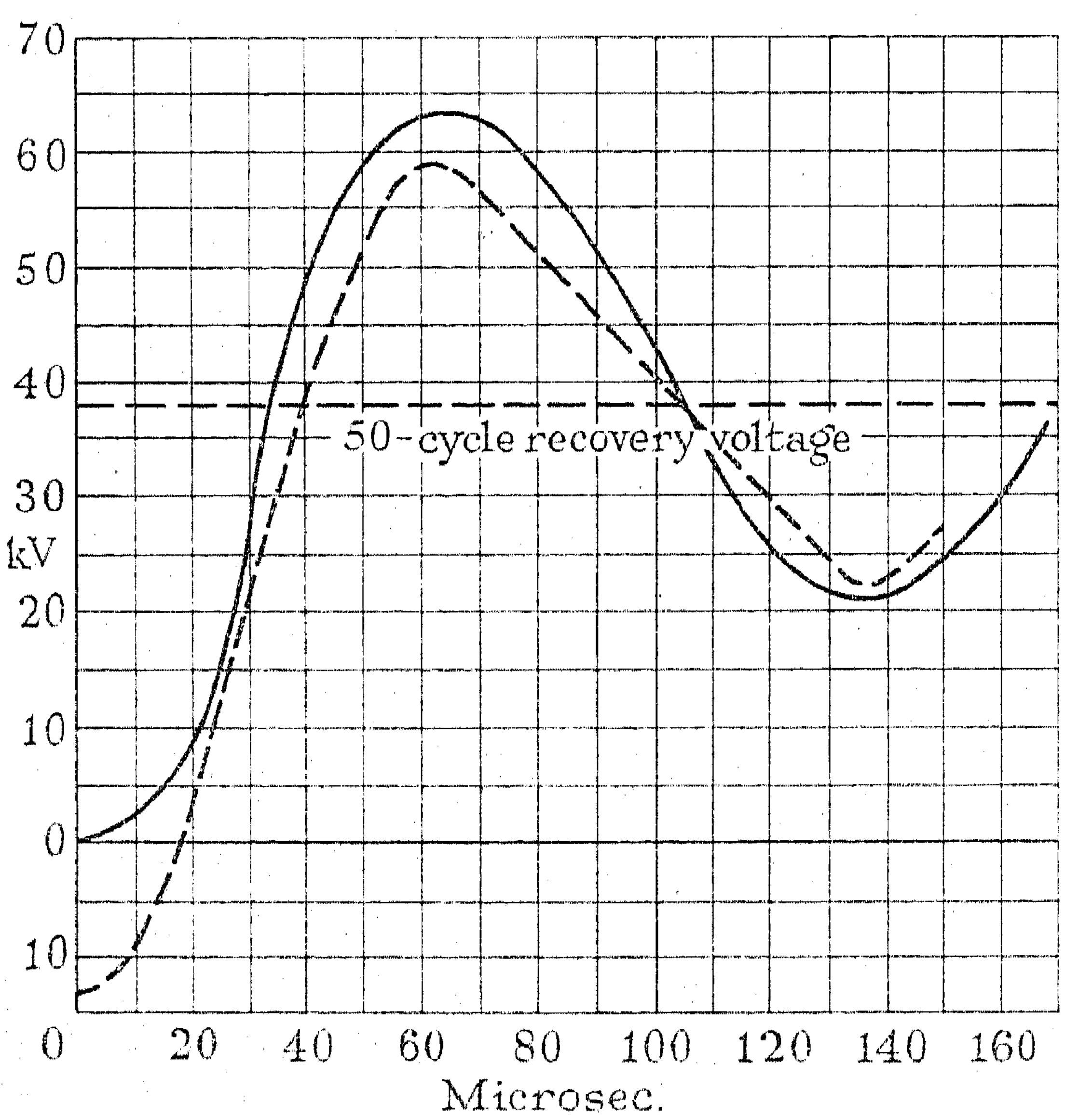


Fig. P

restriking voltage can be affected by the arc voltages of the other phases in the same manner as is described in connection with Figs. N and O.

I hope that my few remarks have made it clear that the author's instrument represents a very valuable "yard stick" in the new field of restriking-voltage research.

Mr. J. Harcourt Williams: How are we going to investigate an actual system until there is some further development of Messrs. Trencham and Wilkinson's instrument which will enable investigations to be carried out while the system is alive? It is not easy to visualize obtaining the desired information from a large system such as that of Manchester, except when it is alive. A large number of oil switches having recently been replaced at considerable cost, one is rather alarmed at the prospect of further examinations which might result in the discovery by switchgear manufacturers of fresh arguments why further expenditure should be incurred by the user.

Mr. A. K. Nuttall: The operation of the instrument described by Messrs. Trencham and Wilkinson is of such a high standard of excellence that one is liable to forget the technical difficulties involved in the development of the circuit. No one who has not worked with circuits involving the high degree of accuracy of synchronization demanded by the present instrument can appreciate the difficulties involved.

The validity of certain equations quoted in the Appendix of their paper appears open to question. For example, the restriking voltage is shown in equation (1) as an operational expression which is subsequently developed as a power series in terms of a function F which is expressed as

$$F \simeq \frac{Z}{L_2(1-K^2)p}$$

Now it is evident that an expression in terms of a power series is meaningless unless it is established that the series in question is convergent; the condition for convergency of the present series is that $F < 1$. Since in the present case Z is itself a function of p of a form depending upon the nature of the circuit under investigation, it appears quite possible that circumstances may arise in which the series ceases to be convergent. The authors themselves quote an instance where the load comprises a pure inductance L, so that $Z = Lp$, and in this case F is given by $L/[L_2(1-K^2)]$. This condition constitutes a simple case in which F is independent of p; the convergency of the power series can now be readily examined. The series is only convergent if $L/[L_2(1-K^2)] < 1$, and, since the value of K may approach fairly closely to unity, it is evident that the ratio L/L_2 may easily assume a value which invalidates equations (3) and (4). Whilst it is probable that in all practical cases the value of the ratio L/L_2 is small, and whilst the inclusion of the parameter C in the operational expression for Z also contributes towards conditions which lead to convergency of the power series under consideration, the value of the analysis included in the Appendix would have been enhanced by a brief statement of the conditions necessary for its validity.

[The authors' replies to this discussion will be found on page 486.]

DISCUSSION BEFORE THE NORTH-EASTERN CENTRE, AT NEWCASTLE, 23RD NOVEMBER, 1936, ON THE PAPER BY MESSRS. TRENCHAM AND WILKINSON*

Mr. P. J. Ryle: So far our knowledge of how a circuit breaker really breaks a circuit is not sufficiently advanced to enable us to say what the effect of the restriking

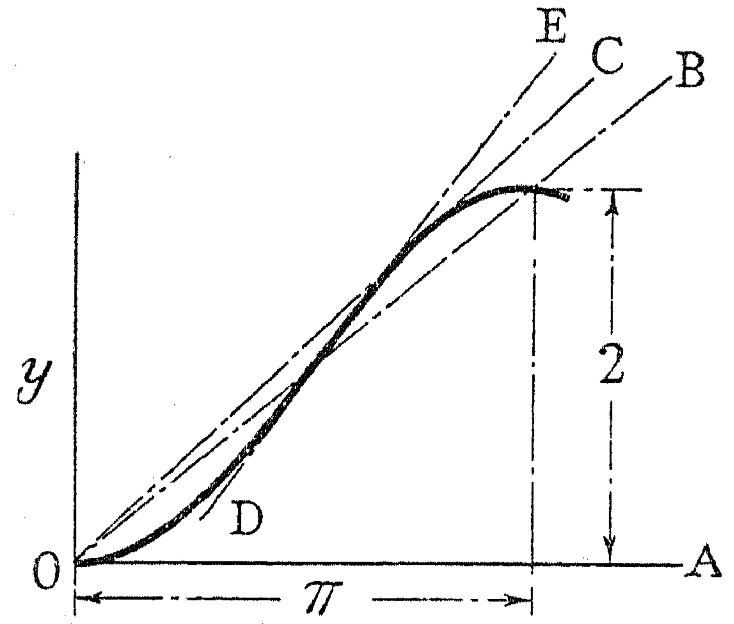


Fig. Q.—Slopes of single-frequency transient.

Slope at $x = 0$, zero (OA).
Mean slope from $x = 0$ to $x = \pi$, 0·636 (OB).
Maximum slope at $x = \pi/2$, 1·0 (DE).
Slope of steepest tangent through $x = 0$, 0·725 (OC).

transient is, and consequently we cannot yet assess the degree of severity to be assigned to any assumed or measured transient. Even if we could state definitely that the degree of severity was some definite function of the rate of rise of restriking voltage, we should still have very considerable difficulty in defining that rate of rise. Most calculated restriking transients for given system points could be sufficiently well represented by double-frequency transients, the two components each having wide ranges of both frequency and amplitude. The wave-shape of the complete transient could then be almost anything.

The simplest form of re-striking transient is the single-frequency one, illustrated by $y = 1 - \cos x$ (see Fig. Q). Now even for this simple shape it is very doubtful what should be taken as the rate of rise or slope. At the

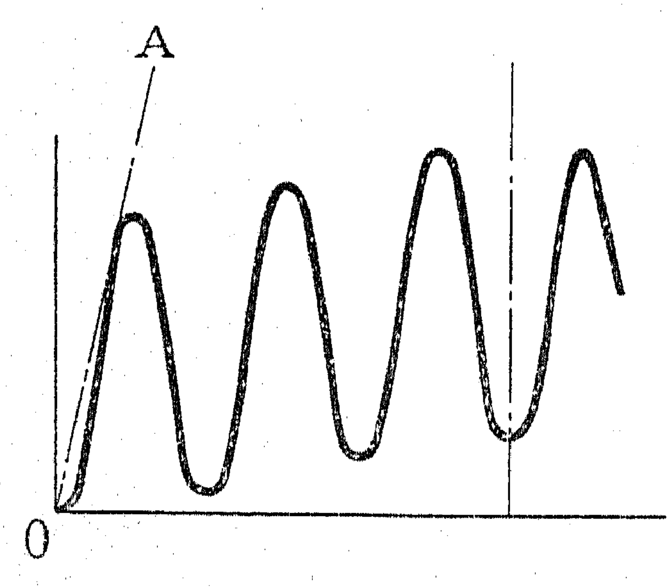


Fig. R.—Double-frequency transient: high-frequency component large compared with low-frequency component.

bottom and top the slope is zero; half way up the slope is a maximum, unity; the mean slope is 0·636; and the slope of the steepest tangent through the origin, a slope often taken as a useful criterion on actual transients in practice, is 0·725.

When we come to double-frequency transients, the slope to take as representing the rate of rise becomes even more debatable. If the amplitude of the high-frequency component is large compared with that of the low-frequency component, the steepest tangent (OA, Fig. R) through the origin seems quite a reasonable choice. If

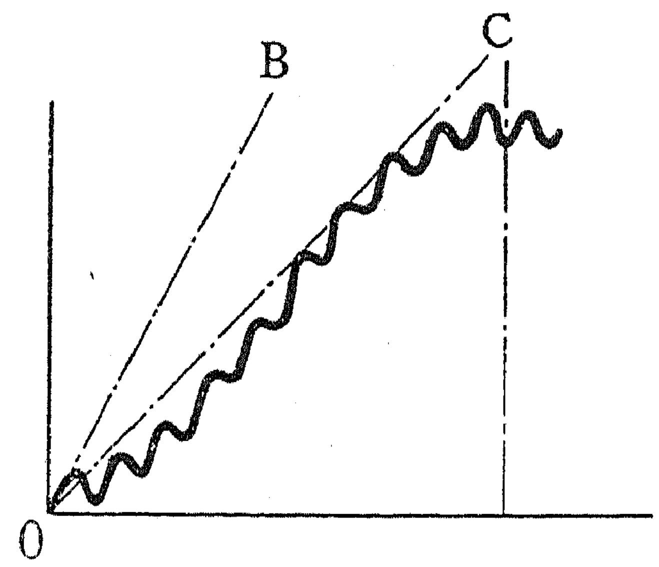


Fig. S.—Double-frequency transients: high-frequency component small compared with low-frequency component.

the respective relative amplitudes are reversed (Fig. S), however, it begins to appear absurd to take the steepest tangent (OB), and something like OC would appear to represent better the conception we have in mind. The absurdity of taking OB would be greater still if, as on calculated transients for many actual service points, the high-frequency component were merely a minute saw-tooth ripple only just visible on the main wave. Perhaps the most difficult case of all is when the high-frequency and low-frequency components are of more or less equal amplitude (quite a practical case). Here OD, OE, or OF (Fig. T) are all worthy of consideration as representing the rate of rise.

I should like to put forward, for the authors' consideration, a suggestion for a rough-and-ready criterion which, whilst having little physical backing, does give a not unreasonable sort of "figure of merit" for the rate of rise, and one which might be of use in classifying and comparing actual or calculated transients of various shapes.

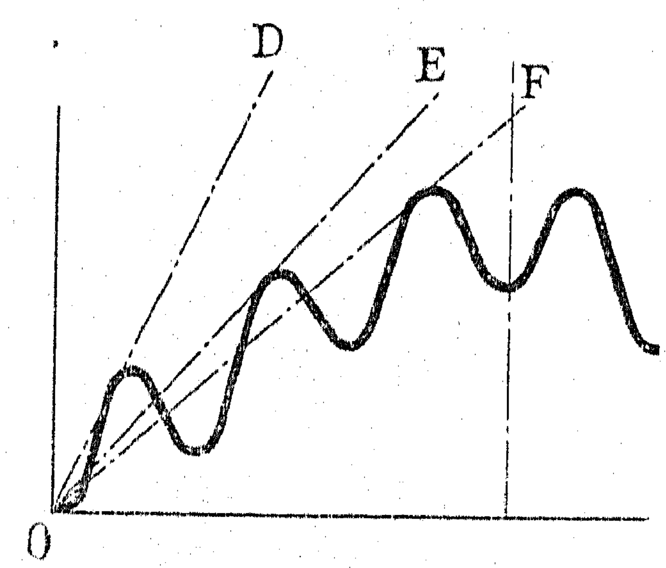


Fig. T.—Double-frequency transient: high-frequency component comparable with low-frequency component.

The suggestion is a weighted mean of the slope of the steepest tangent through the origin and the average slope of the whole transient to the peak. Thus, in Fig. U, OG is the steepest tangent, of slope s_1, and recorded at an amplitude a_1. OH is the line of mean slope (s_2) to the peak and is associated with amplitude a_2. Then the proposed expression for the overall rate of rise is $(s_1a_1 + s_2a_2)/(a_1 + a_2)$. This gives a reasonable result for most general types of transient. For instance, if the

* See page 460.

high-frequency component is of negligible amplitude, the expression gives s_2 as the slope. If the high-frequency component is of very large amplitude compared with the low-frequency component, the expression gives s_1 as the slope.

On page 460 the authors state that the conditions as regards rate of rise are usually more severe in the test plant than in service. Nevertheless cases do arise where this is not so. I remember a case of a fairly small circuit-breaker destined for a position with little cable or other capacitance. For the tests, the reactance had to be large in order to restrict the fault current to the required value, and the irreducible self-capacitance of the test-plant generator and its connections made the natural frequency, and consequently the rate of rise, less than that calculated for the service destination of the breaker. Attention is drawn to this subject in a recent article by Hameister,* from which it appears that it may not be at all unusual for the test-plant severity condition to be easier than that of service.

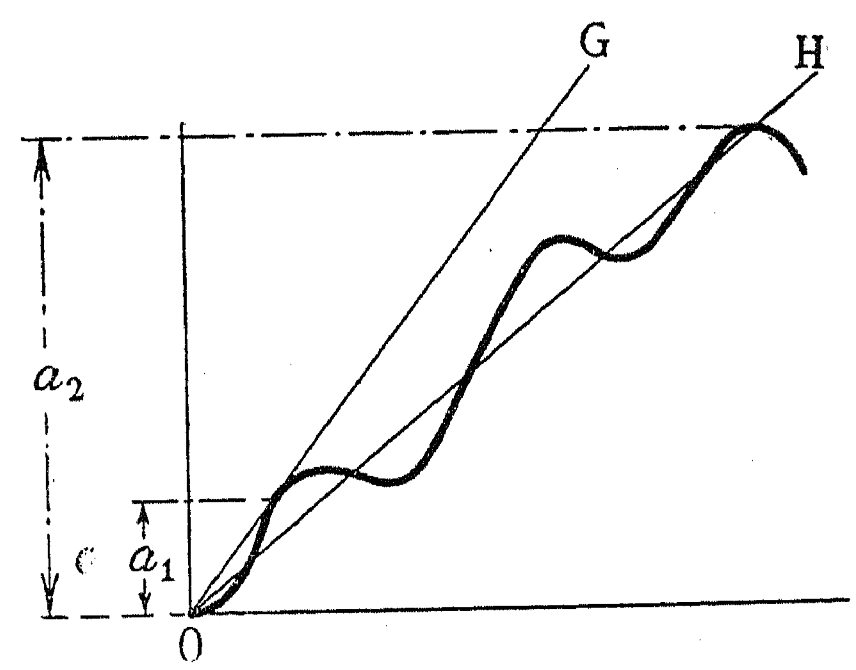


Fig. U.—Typical transient.

Mr. J. A. Harle: The restriking-voltage indicator will be a very useful tool for short-circuit testing stations in that the inherent restriking-voltage oscillations of the test circuit can be thereby demonstrated prior to a test and the records so obtained compared with those of the cathode-ray oscillograph recording the restriking voltage during the test. Unfortunately its sphere of application on customers' systems is restricted to locations where the local circuit can be completely isolated and made dead. Further, the effect of loads on the system will influence the rate of rise in many cases, and hence the value recorded on an unloaded system may be rather pessimistic.

Earlier methods of exploring such circuits for oscillatory frequencies by other than actual circuit-breaker tests consisted of determining the various frequencies by resonance methods and assessing from these frequencies the curve of the restriking voltage that would occur in practice. Unfortunately the percentage voltage associated with each frequency was not so easily assessed and hence the resulting value was very arbitrary. I welcome the authors' device as a very useful step forward from such methods.

I would confirm their view of the difficulty of assessing the values to give to the restriking voltages recorded when making comparisons of circuit severity, especially as they point out that the value that would be a comparison for one circuit breaker would not be for another. There is no question, in my opinion, that any limits standardized for rate of rise of restriking voltage must be accompanied by limits for the amplitude of the restriking voltage, as certain types of breakers are susceptible to the amplitude of the restriking voltage wave. It is also possible that the energy associated with certain of the oscillations may have an effect in determining whether restriking shall occur, and in consequence the complexity of the problem increases.

Users should be extremely careful when considering rates of rise on their systems, as, whilst the restriking voltage of a location may be such that low frequencies are associated with it when the fault current is controlled by the system impedance, when the fault current is controlled by a transformer impedance or a reactance at the location very high frequencies can be present on breaking the fault current in such a circuit. Under this condition high recovery voltages will be present with low current values, and in consequence the severity of the circuit may be practically equal to that usually associated with a testing station.

Mr. H. W. Clothier: Judged on the experience of the past, and particularly on occurrences in recent years, the factor of first importance in regard to switchgear is the constant maintenance of insulation dielectric so that it may be capable of withstanding all voltage phenomena occurring in service. The majority of troubles in service have their origin in one form or other of insulation breakdown. Next in importance is the ability of protective gear and circuit-breaking devices to function correctly according to the nature and position of the fault, in order to limit the extent of damage resulting therefrom.

Thanks to the work of the I.E.C. in the preparation of a new specification, the industry generally is now realizing how the satisfactory performance of a rating is dependent upon a number of factors that may vary considerably in several situations on a transmission and distribution system, so that what was known as a certain kVA breaking-capacity in the past may be far from giving that performance under the more complete specification of to-day.

The authors' work has emphasized one of these factors, namely the rate of rise of restriking voltage. For some time experts have been seeking means of comparing testing-station severity with actual service severity, and, thanks to the co-operative spirit of the E.R.A., some tests have been made in England on a 6 000-volt system and on a 33 000-volt system under service conditions. Such tests, however, are very expensive and so difficult to make that very few supply authorities are willing to co-operate in this research. The authors' work, in an endeavour to ascertain the measurement without imposing an actual fault on a system, is an invaluable step in the right direction; but before the measurements obtained by an instrument can be accepted in substitution for short-circuit field tests it will be necessary to take the further step in the development of making it possible for the measurements to be made when the system is alive under actual service conditions of connections and load.

Mr. R. H. Brierly: I should like to ask the authors whether they have made an actual comparison between

* *Elektrotechnische Zeitschrift*, 1936, vol. 57, pp. 1025, 1052.

records of the restriking voltage in a given circuit, as obtained from the instrument described in the paper, and on a cathode-ray oscillogram.

It is appreciated that, as the authors point out, the form of the restriking voltage is affected by the operation of the circuit breaker used to break the circuit, on account of such factors as current suppression, arc resistance, and post-arc conductivity, and that therefore cathode-ray oscillograms recorded in conjunction with a commercial circuit breaker do not give the true inherent characteristics of the voltage transient. In certain forms of arc-control device, however (e.g. the Turbulator), the influence of arc resistance and post-arc conductivity is reduced to a minimum for the normal frequencies met with in testing stations, and therefore a circuit-breaking device employing such means of arc control approaches to the ideal device for use in conjunction with a cathode-ray oscillograph.

A comparison between the records given by the authors' instrument and cathode-ray oscillograms, taken in conjunction with a circuit-breaking device in which the above factors are reduced to a minimum, would form a useful practical check on the accuracy of the instrument.

[The authors' reply to this discussion will be found on page 488.]

DISCUSSION BEFORE THE NORTH-EASTERN CENTRE, AT NEWCASTLE, 11TH JANUARY, 1937, ON THE PAPER BY PROF. THORNTON*

Mr. J. A. Harle: It is important to remember that the circuit on which the author's experiments were carried out is non-inductive and hence the voltage causing the restriking at the gap immediately after the current zero is relatively small compared with that in inductive circuits, rising to its maximum in 0·005 sec. or $\frac{1}{4}$ period. Thus there is appreciable time for the gap to regain adequate electric strength after the current zero, and so to prevent restriking contrary to the general conditions standardized for normal circuit-breakers where the voltage rises to nearly twice its peak value in a short time determined by the natural frequency of the test circuit.

Research carried out many years ago with direct currents indicated to me that there was a threshold condition for arcing to take place, from which it appeared that, unless the certain minimum current value was reached for each voltage, no arcing as such took place and the circuit was opened with what may be termed a "break" spark, i.e. a discharge that is not self-sustained. My conclusions on this were that for each voltage there appeared to be necessary a minimum energy-release which would cause the contact spot to heat up to an adequate temperature for the electric field to produce a discharge having true arc characteristics. If a.c. arcs are considered on this basis it appears that, provided the point of final current flow in the gap preceding the current zero is cooled down at such a rate that the build-up of the voltage during the next half-cycle is inadequate to restrike the gap, extinction is to be expected.

If we consider the author's theory that extinction takes place largely owing to the force of repulsion between the electrons, this phenomenon will be expected to take place progressively during the falling part of the current wave until finally, at the current zero, the last electrons in the gap will repel and the arc will be extinguished. Will not this repulsion be taking place in all a.c. arc paths during the falling portion of the current wave? Some other feature may thus be necessary to account for the micro-gap switch extinction in addition to that of repulsion. Is it that the gap voltage is low enough to prevent an arc crater forming? If this is so, does not the contact-cooling action provide the additional argument for break, together with the very slow build-up of the restriking voltage wave? From the author's oscillogram (*a*) there appears to be no doubt that the device has a true arc characteristic during current flow, and the flatness of the voltage characteristic is indicative of a very restricted arc path.

Mr. S. A. Simon: In oscillogram (*a*) three lines are shown, but on (*b*) and (*c*) there are only two. What does the third line represent, or what is the explanation of the difference?

Mr. M. Waters: The micro-gap switch is only suitable for interrupting currents at unity power factor, and it has been suggested that the inductance of the main generator and step-down transformers might adversely affect the operation of the switch. This, of course, will not be so, since under normal load conditions the resistance of a unity-power-factor load such as might be switched on by the largest micro-gap switch will be so high that the effect of the inductance will be quite negligible, and on opening the circuit the recovery voltage will be almost in phase with the load current interrupted. Thus when the current is finally extinguished at a zero point the voltage will also be at the zero point, and there will be no voltage "kick" to start the circuit oscillating.

Referring to the actual operation of the micro-gap switch, I should be pleased if the author would explain what part is played by ions in the arc before current extinction. Would it not be possible to explain the operation of the micro-gap switch by assuming that the arc conduction is mainly ionic and that recombination is sufficiently rapid during the zero pause to cause the arc to be extinguished? This would have to be accompanied by sufficiently rapid cooling of the electrodes to ensure that no emission of electrons was possible by the time the voltage rose again.

Mr. E. Anderson: In tests carried out by Mr. J. Anderson some years ago it was found easily possible to interrupt 600 amps. at 400 volts, 50 cycles per sec., with a $\frac{1}{16}$-in. break. A breaker with 10 breaks per pole dealt with 32 amps., 5 000 volts, 3-phase, very easily. The breaks, each of 0·006 in., occurred one after the other. Similar results were also obtained with simultaneous break. Immersion in oil does not give improved performance, a fact which seems to support the author's theory of the micro-gap switch.

[The author's reply to this discussion will be found on page 486.]

* See page 457.

THE AUTHORS' REPLIES TO THE LONDON, MANCHESTER, AND NEWCASTLE DISCUSSIONS

Professor W. M. Thornton (*in reply*): Mr. Satchwell has shown the necessity for a "snap" break to obtain the best working conditions for a micro-gap switch. It is interesting to hear from him that the switch works well even on low power factors. Mr. Flurscheim's remark that such switches only fail by contact-welding goes to the root of the matter, and for such welding to occur large currents are necessary.

Dr. Whitney asks whether the current and voltage were exactly in phase in oscillogram (a). They were, to the thickness of the lines of the oscillogram. The slight curvature of the current line as it falls to its final zero is undoubtedly damping of the oscillograph strip. It is not found in cathode-ray oscillograph records of the same break. From the many records taken, I believe that if the circuit were opened exactly as the current passed through zero—and this rarely happens in practice—the air in the gap would remain in a conducting state long enough to enable the arc to restrike.

In reply to Mr. Ockenden, the figures quoted by Mr. Flurscheim show how remote is the possibility of the contacts building up with the working currents for which the switches are used. The essential feature of the switch is that the path of the current in the gap widens so rapidly that local pitting or building-up does not occur.

The Telefunken arc referred to by Dr. Rayner worked at much higher frequencies than 50, and was certainly very efficient. The power factor was low, and other speakers have shown that the use of the switch is not to be confined to high-power-factor heating circuits. It works equally well over the whole range of load.

I agree with Mr. J. K. Brown that the performance of these micro-gap switches is so interesting that further research on their voltage-recovery characteristics would be worth while. My reason for thinking, apart from the oscillograms, that it is better to break a circuit a little before zero pause is that any (in this case small) oscillations due to the opening of the gap are superposed on a circuit voltage that is falling rather than rising, as it would be if the break were at zero.

Mr. Bernard discusses direct-current circuits. The great point in lessening the break spark in such a circuit is to prevent the voltage from rising rapidly in the gap at the instant of break. The use of a condenser across the gap does this with great success, as he mentions. Mr. Woolnough, I think, forgets that when the gap is small there is a very small voltage-drop across it. The current is flowing and about 95 per cent of the voltage is in the circuit outside the gap.

The special feature of vacuum switches is that there is little or no dynamic resistance of the air to the expansion of the momentary arc at break. For this reason the flash is much larger in a mercury-vacuum switch. Mr. Pearce is under the impression that the switch works in a vacuum. This is not the case. The force between two electron streams or currents flowing side by side is a repulsion until the velocity equals that of light, and this of course it never approaches in switchgear. The rise of voltage as the arc persists, though the current is falling, is caused by the fall of the current density in the gap, owing partly to the decrease of current, and partly to the spread of the arc. There is, of course, the effect mentioned in the paper of the cooling of the surface in contact with the arc owing to the spread.

Dr. Dannatt's suggestion that there is a rapid neutralization of the positive space charge in the layer of gas at the cathode surface would be, I think, correct if there were ionization by collision in the gap. I doubt, however, whether this occurs at the voltages across the gap while the current is flowing. When the break is complete, there is not sufficient ionization to cause the arc to restrike. Mr. Farrer's figures are interesting, though measurements of the electric strength of air by spark discharges between small spheres are not regarded as reliable. There is, as he says, a satisfactory margin of safety in the gaps used.

Mr. Harle's researches on direct-current breaks, which were carried out in my laboratory at Armstrong College, showed conclusively that there are two stages in a break spark and that there is a sharp division between them. The second or "arc" stage is undoubtedly due to the electron emission from one of the poles reaching a critical value. From this onwards the discharge has a true arc characteristic. It is therefore probable that this is the transition point in the type of discharge where the ionization by collision that gives rise to a simple "break" or "jump" spark is overshadowed by the thermal ionization emitted from a hot spot on one of the contacts. In the paper there is no claim that repulsion between ions and electrons is the whole action in the microgap, but it does explain why such a gap is so effective in breaking relatively large currents even if—as the discussion has brought out—they have a power factor less than unity.

In reply to Mr. Simon the line that continues across the oscillogram is a zero line carried around the film drum.

Mr. Waters's question as to the part played by ions can be answered by the fact that the arc is visible and that therefore there must be atoms in it in vibration and so, to some extent, molecular ions. There is no doubt that the recombination of ions and the cooling of the electrodes play a part in the rapid extinction.

Mr. Anderson's figures are very interesting. Most of the high-tension multiple breaks that have been tried from time to time have gaps of the order of $\frac{1}{16}$ in. mentioned by him. These are not microgaps of the order considered in the paper, where the separation is at most a few thousandths of an inch. It might be worth repeating the tests of multiple gaps with separations of the latter order.

Messrs. H. Trencham and **K. J. R. Wilkinson** (*in reply*):

London.

As regards Mr. Flurscheim's suggestion that there is in the paper a lack of new ideas on the effect of restriking voltage on circuit breakers, we tried to emphasize a point which, though perhaps it had occurred to some, has certainly not received general recognition, namely that we cannot even begin a useful classification of restriking-voltage severity until the insulation build-up in circuit breakers is explored to a considerably greater extent. As lending point to this comment, one of the authors was present at a long and heated discussion between certain engineers on the relative severity of symmetrical as against asymmetrical current in circuit-breaker operation. Each party claimed that tests had proved his view correct and neither realized that both results could be obtained, depending on the relationship between insulation build-up and restriking voltage. If the build-up of insulation were quick enough, arc extinction would occur at the first zero in both types of test and one current loop only would contribute to arc energy; thus, by reason of its greater peak value and duration, the asymmetrical condition would be more severe. Some lower rate of insulation build-up might permit only one asymmetrical current loop but several loops of symmetrical current, because of the higher rate of rise of restriking voltage in the symmetrical case, and in this event the tax on the breaker would be more severe with symmetrical current.

We can confirm the tendencies described by Mr. Flurscheim as disclosed in the tests reported by him, and agree with him that there is much ground to be covered in the solution of the main problem. A series of systematic tests might well form the basis of a complete paper on the subject.

The work of examining the restriking voltage indicator which Mr. Gosland has carried out for the E.R.A. forms a valuable confirmation of the accuracy claims made for it in the curves of Fig. 4. This work also agrees in finding that the transient response of a generator is a function of field excitation of the type to be expected from low-frequency experience, namely a reduction of inductance with increase in excitation.

We have suggested in the paper that where the generator forms an appreciable part of the circuit impedance under review, it will be advisable to test under working conditions of excitation. Mr. Gosland's suggestion that the restriking-voltage indicator should be made suitable for live-circuit testing is an attractive one and one to which we hope to devote some attention.

In reply to Mr. V. A. Brown, the possible effect of shunt load in easing the duty on circuit breakers when interrupting faults is a matter of considerable interest. It is one also which must be regarded with some qualification, because in order to exert efficient damping the load must be resistive (as distinct from mechanical) and it must be closely coupled to the breaker terminals.

Mr. Brown's suggested method of recording restriking voltage as peak value divided by the time to peak is somewhat similar to the method used by us in classifying Figs. 7 A to G.

We appreciate the support given by Mr. Garrard to our contention that there is a real need for a carefully planned programme of systematic research, in order to establish a fund of sound information concerning the exact phenomena in circuit breakers when effecting the interruption of a circuit.

Regarding the value of the indications given by the restriking-voltage indicator, Mr. Garrard seems to have doubts as to their accuracy because of the differing values of current and voltage used therein, as against those occurring in practice. The ground for these doubts is not fundamental, as is shown elsewhere in this discussion, because the inherent restriking-voltage characteristic in any location is determined by circuit constants which are largely independent of current and voltage.

An indication by the restriking-voltage indicator taken with all apparatus in position will, within the limits of the instrument error, be a true record of the restriking-voltage conditions inherent at any given location, and any difference between such an indication and that obtained by, for example, a cathode-ray oscillograph during circuit interruption will be occasioned largely by the operating characteristics of the circuit breaker itself. We believe that this represents a feature of great value from the point of view of research.

In answer to the questions concerning Fig. 7, the time scale is indicated by a 100-kilocycle timing wave on each of the oscillograms. "Maximum theoretical amplitude" is taken as twice the instantaneous recovery voltage at its peak, i.e. the highest point attained by an undamped oscillation swinging from zero about this recovery voltage value taken at zero power factor. The values were omitted from "C" because the curve to give amplitude calibrations had not been photographed, and the oscillation due to so large an added capacitance was so slow that the indication was of no quantitative interest. The values tabulated for "B" are those applying to the maximum value, i.e. to the second peak, and the first peak might be as important or not, depending on the circuit-breaker characteristic. Capacitance of the secondary of the injecting mutual inductance M has been considered in the design of this coil, with the result that for no range is the distortion due to this cause greater than would be occasioned by a capacitance of 90 $\mu\mu$F placed in parallel with the breaker under test. Since few high-voltage bushings have so low a capacitance, it will be appreciated that the effect is small compared with that of the breaker capacitance itself.

The instrument, when used on supplies of average steadiness and without an auxiliary generator, yields an image suitable for photographic reproduction.

Mr. J. K. Brown states that for several years investigations have been in progress to establish the effect of rate of rise of recovery voltage on circuit breakers. Whilst the significance of restriking-voltage severity may not as yet be fully comprehended, it is at least important to investigate the subject fully in order to know its true reactions in circuit-breaker operation.

Regarding Mr. Brown's comments on a limiting natural frequency of 3 kilocycles, above which breaker operation is dependent only on the amplitude of restriking voltage, we doubt whether there is yet a sufficiency of evidence to warrant this conclusion, and

apparently Mr. Brown is of the same opinion since he is later concerned with the analysis of the restriking voltage at higher frequencies.

We would agree with Mr. Brown that considerable difficulty is involved in analysing into its harmonic components a restriking voltage wave of which frequency values cannot readily be distinguished. This is particularly true with complex and highly-damped circuits. While special methods are available for analysing such waves, we doubt the utility of the operation where it is performed for the purpose of predetermining the restriking voltage of a composite circuit formed of known component circuits.

A knowledge of circuit conditions in itself will be of little assistance in providing the information mentioned by Mr. Knowles, for the behaviour of the breaker is settled by its own characteristics reacting with those of the circuit. In the extreme case the changed conditions may conceivably be such as to overtax and wreck the circuit breaker.

It is gratifying to hear that Dr. Whitney has already given some attention to the varying behaviour of different arc-control devices under similar circuit conditions, and to the subject of restriking-voltage characteristics on live systems.

The care and attention given by the E.R.A. in carrying out their investigations, and the diligence with which the data obtained are sifted for relevant information, give their work a definite value, and the publication of results foreshadowed by Dr. Whitney will be awaited with great interest.

Mr. Ockenden raises a number of interesting points. Steadiness of the image is of great importance where photographs of some 200 or 300 successive superposed images are required. Experience showed that, given absolutely steady supply conditions, an average thyratron would indeed trip consistently within one or two microseconds, but for steadiness under normal supply conditions, use has been made of a peaking transformer, the bulk of the excitation for which is derived from a winding in series with the scanning coil. By this means a steadiness of image is obtained which is quite suitable for exposures of several seconds, when using mains supply of normal steadiness.

It is to be emphasized that thyratron tripping is in this way synchronized not with the somewhat vague position of peak voltage but with the instant of zero flux in the scanning coil—a much more precisely defined instant, and one, moreover, which controls spot position. By using a sufficiently peaked grid voltage, variations of anode voltage are arranged to be relatively unimportant in controlling image position. The thyratron conducts during practically a full half-cycle, and not a quarter-cycle as mentioned by Mr. Ockenden, because the load is effectively inductive. Errors due to arc voltage and to coil resistance serve slightly to curtail the shape of this half wave, but only at times which are remote from the important initial period.

Manchester.

Mr. Pearce is not alone in calling attention to the additional advantage which would attach to the restriking-voltage indicator were it suitable for application to live circuits. In reply to this point we have had it in mind from the commencement but, not finding a solution of the problem of live operation readily available, it was felt nevertheless that there was much benefit possible from the use of the instrument in its present form. If the completely universal application is developed, its extended utility is unquestioned.

In reply to Dr. Dannatt, check tests have not been carried out against calculated circuits, except for circuits containing lumped constants and having very much less complexity than transformers. Our developments in the direction of live-line testing are not yet sufficiently advanced to warrant description.

Messrs. Brown and Ehrenberg have been very kind in supplementing information given in the paper concerning the behaviour of the restriking-voltage indicator in test-station service. It is interesting to note that in Figs. N and P full-scale tests tend in each case to show a greater percentage of harmonic than the restriking-voltage indicator. This is in accordance with the characteristic behaviour of complex circuits in exaggerating harmonics where appreciable pre-zero arc drop or current suppression is present. It is felt that with the gradual accumulation of test records, data will be provided for assisting in the exact solution of many problems which at present have no answer or can be answered only in vaguely descriptive terms.

Regarding the application of the restriking-voltage indicator to existing systems as mentioned by Mr. Harcourt Williams, so long as live application is not possible the situation can be met only by making the system dead. Where a large part of a system is involved, this is of course a serious limitation, but in locations remote from the generating station the more effective parameters of the restriking-voltage characteristics tend to reside in those parts of the circuit which are nearby and which can therefore more probably be isolated.

In general, additions and extensions to a distribution system, particularly a cable system, should by increase in capacity tend to ease the severity of duty on the circuit breakers, provided they are otherwise properly selected for their task.

Mr. Nuttall questions the validity of expressions involving F. The mathematical treatment in the Appendix must not be considered apart from its context, which is the examination of a "constant current" generator, or one in which the load voltage, i_2Z, is deliberately made small compared with the internal generated e.m.f., $i_2[L_2(1 - K^2)p + Z]$. Thus, while it is not expressly stated, the condition for validity is nevertheless implied, namely that the "error fraction" F shall be less than unity, and in the actual application F is indeed limited for each range of the instrument to a few per cent.

Newcastle.

Mr. Ryle's formula, which expresses the mean product of amplitude and slope, forms a simple, plausible, and therefore useful, basis for discussion. As he clearly states, such expressions cannot yet claim to have a satisfactory physical backing, and it rests for experience of circuit-breaker operations in known circuits, together with such

advances as may be made in determining the build-up of insulation strength between circuit-breaker contacts, to give confirmation of the extent to which such formulae can be accepted as representing circuit severity.

His comments, and those of other contributors to the discussion, are welcome in that they demonstrate a sufficient appreciation of the facts involved to secure against the blind acceptance on the one hand of the indefinite term "natural frequency" of the circuit, referred to by many earlier writers on the subject of circuit severity, and on the other hand of the rate of rise expressed as the slope to some arbitrary point on the wave. Being assured of this reservation of judgment we can now await the results of system tests and their analysis, having regard to the circuit-breaker action, to give us reliable data on which to base logical conclusions concerning severity. Mr. Ryle's reminder is also timely, that, in practice, cases of abnormally high severity may occur, and a knowledge of this, together with a more general appreciation of how the conditions are brought about, will doubtless lead to their avoidance where this is possible, or to special steps for meeting them when they may be inevitable.

It is only recently that attention has been drawn to the additional point raised by Mr. Harle in that capacitance which may be instrumental in determining the form of the restriking-voltage characteristic may also act as a temporary reservoir of energy which will tend to maintain conductivity in the arc. However unwelcome this additional complication may be, it is one which must be faced. We believe that the Electrical Research Association is already taking cognizance of it in their investigations into the fundamentals of circuit interruption.

We are entirely in accord with Mr. Clothier in ascribing to the subject of insulation a position of supreme importance in electrical power supply. As touching circuit breakers, the subject of insulation strength has already been agreed as a fitting one on which to prepare a companion I.E.C. specification to that on rating mentioned by Mr. Clothier, and there is no doubt that international agreement on such an important matter will be all to the good.

The operation of the restriking-voltage indicator on live circuits has been referred to earlier in this reply, and the desirability of live-circuit testing is in no wise questioned. It is of some help that one side of a breaker, namely that on which a fault is assumed to occur, would in most circumstances remain at earth potential in order to simulate the fault and to prevent those circuit characteristics beyond it from exerting a' unwanted influence on the reading of the instrument.

Mr. Brierly's question can best be answered by reference to some of the information kindly supplied by Mr. Gosland of the E.R.A., and illustrated in Figs. D to K inclusive. As already emphasized, differences between the true inherent restriking voltage and the reading of an oscillogram taken while opening a fault are entirely bound up in the operating characteristics of the circuit breaker. For example, the effect of pre-zero current suppression is not shown on the restriking-voltage indicator, but in our experience a circuit breaker which gives bad chopping of this kind may occasion pronounced voltage surges on apparatus near it. The comparison suggested by Mr. Brierly is in general a useful check upon the instrument, but may be extended to form a more valuable check on the operation of circuit breakers in general.

A NOTE ON VOLTAGE INSTABILITY IN TESTING EQUIPMENT*

By PROFESSOR B. L. GOODLET, M.A., Associate Member.

(*Paper first received* 21*st September, and in final form* 19*th November,* 1936.)

A phenomenon sometimes encountered with high-voltage testing transformers is the sudden jumping of the output voltage from a low to a high value or vice versa, for a disproportionately small movement of the voltage regulator. Two cases of such instability which recently came to the author's attention are discussed below.

CASE 1

A single-phase testing transformer designed for 75 kV (peak), at 800 volts on the primary, had its high-voltage terminal connected to two thermionic rectifiers arranged to produce $\pm$ 75 kV direct voltage to earth by means of the well-known Greinacher circuit. To limit the current when a short-circuit occurred on the d.c. side, an iron-cored choke was placed in the earth connection to the transformer; the primary voltage of the latter was controlled by an induction regulator (Fig. 1). The d.c. equipment is mentioned only to indicate why the choke

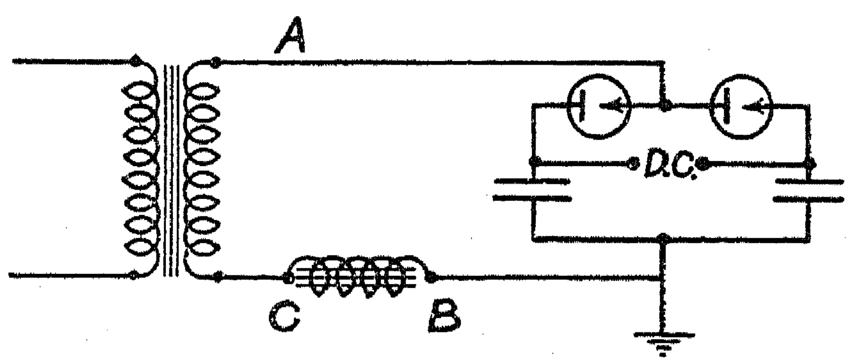


Fig. 1

was employed; the only circuit elements essential to the phenomenon in question are those shown in Fig. 2.

With the earth connection at B (i.e. with the transformer earthed through the choke) it was found that on raising the primary voltage the secondary voltage at first increased only very slowly. When, however, the primary voltage reached about 466 volts the voltage between the terminals A and B suddenly jumped from about 18 kV to 77 kV (peak). After this jump the voltage could be easily varied in both directions along the upper curve (Fig. 2), but if the primary voltage fell to 375 volts a jump back to the lower curve occurred. If the earth connections were made at C instead of at B no jumps occurred, the voltage between A and B being directly proportional to the primary voltage, as shown by the dotted line.

The phenomenon was finally proved to be an example of the peculiar resonance effects which can occur when a condenser is connected in series with an iron-cored choke coil. The relation between the current flowing through such a coil and the voltage developed across it is governed by its magnetization characteristic. For any given current I the fundamental-frequency voltage across the coil will have two components, one leading the current by 90° and of magnitude E_L, and one in phase with the current and of magnitude RI, where R is the effective

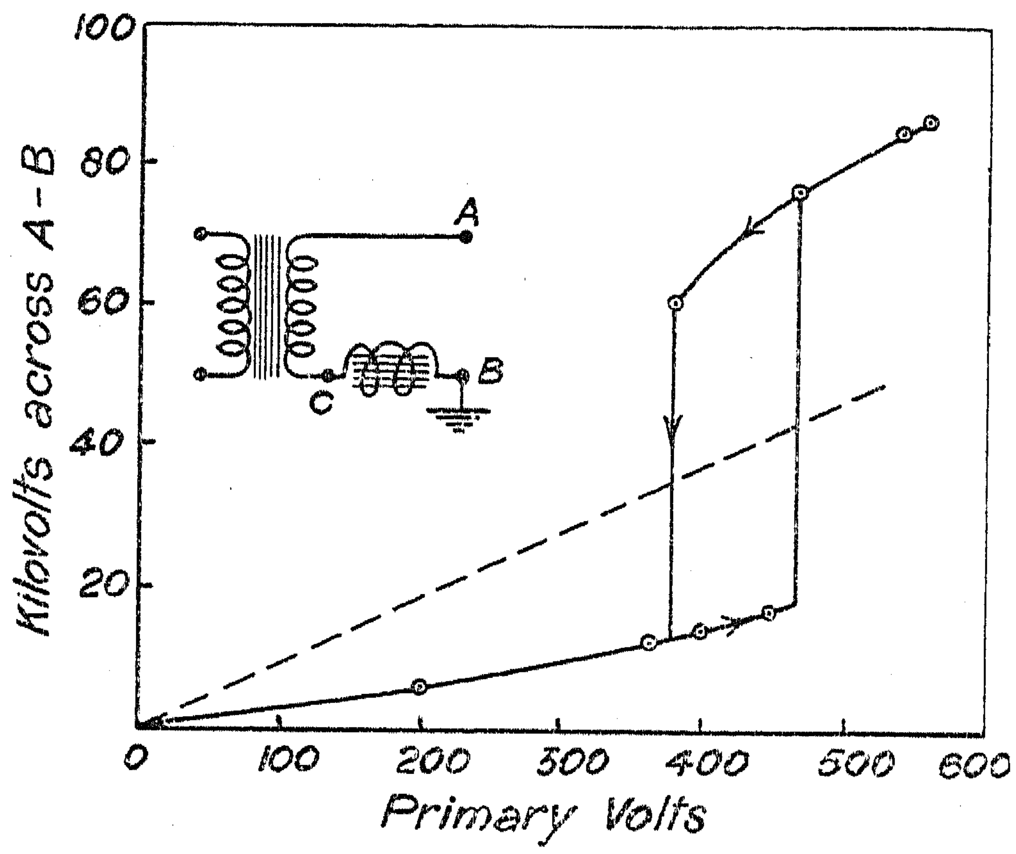


Fig. 2

resistance of the coil under the given conditions. The voltage E_L as a function of the current I is shown in Fig. 3 as the curve obb_1. If now a condenser of capacitance C is placed in series with the coil the current

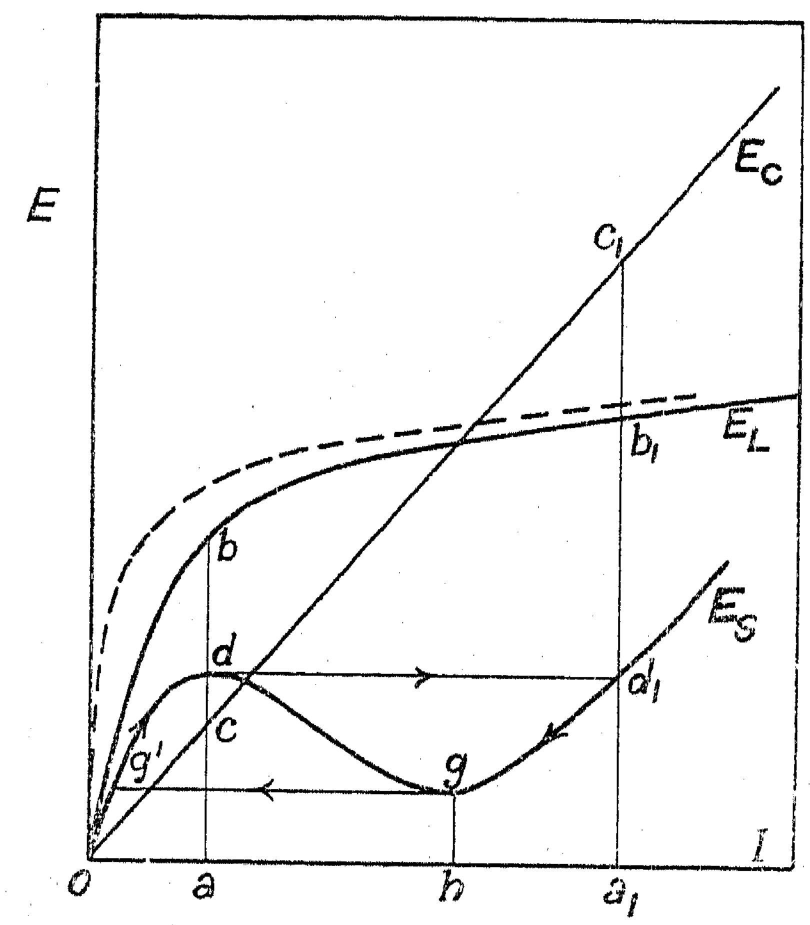


Fig. 3

in it must be the same. The condenser voltage E_C for any current I is given by the straight line occ_1, the equation of which is $E_C = I/(\omega c)$.

The voltages E_L and E_C are of course opposite in phase. To circulate a current I through the combination

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

the applied voltage E_S must therefore consist first of a term $(E_L - E_C)$ in leading quadrature to the current, and second of an in-phase term RI which supplies the losses

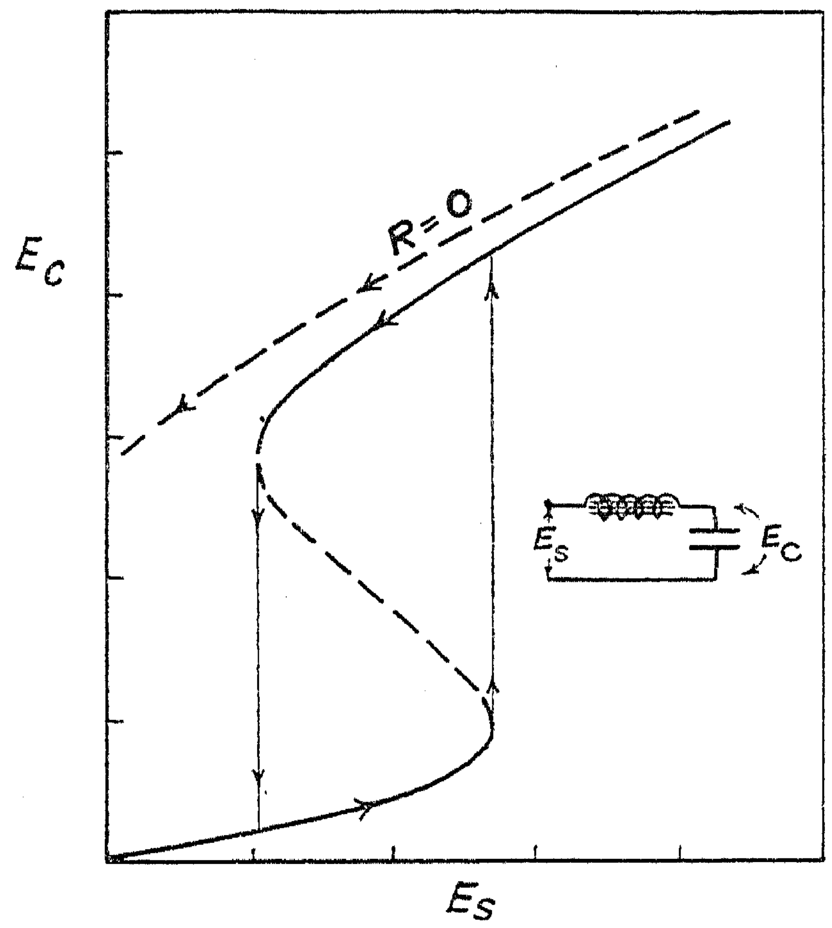


Fig. 4

in the circuit. The absolute magnitude of the supply voltage required is therefore

$$E_S = \sqrt{[(E_L - E_C)^2 + (RI)^2]} \quad . \quad . \quad . \quad (1)$$

$(E_L - E_C)$ is the difference in ordinates between the curves E_L and E_C. Thus for a current represented by oa,

$$(E_L - E_C) = ab - ac = bc$$

As the current increases from zero, $(E_L - E_C)$ at first increases, attains a maximum (at oa), and then commences to decrease. The values of the supply voltage, calculated from the two curves and equation (1), are plotted as the curve E_S or $odgd_1$, which is the volt-ampere characteristic of the combination.

Suppose that the amplitude of the applied voltage is gradually raised from zero. The operating point then moves along the curve od. When the point d is reached the operating point cannot move along dgd_1, since the applied voltage is already ad and is increasing. The operating point therefore jumps from d to d_1 and continues to move along the curve d_1E_S; this jump is accompanied by a sudden reversal of phase.

At the point d the condenser voltage is ac; at the point d_1 it is a_1c_1, which is about 4·3 times as great. The jump d to d_1 is therefore accompanied by a large increase in the condenser voltage.

Suppose now that, with the operating point initially at d_1, the applied voltage is decreased. The operating point then moves down the curve d_1g. At g the voltage $(E_L - E_C)$ is zero and the applied voltage is equal to RI. If, therefore, the resistance is very small, g will almost coincide with h. Further decrease of applied voltage will cause the operating point to jump from g to g', with a corresponding decline in the condenser voltage. The variation of the condenser voltage as a function of the applied voltage is shown in Fig. 4. The effect of increasing the circuit resistance is to decrease somewhat the maximum voltage on the condenser and to narrow the range in which two values of condenser voltage are possible. The effect of changing the frequency instead of the applied voltage is a case of minor practical importance which can be easily worked out by the reader. Naturally, "jump" phenomena will not occur if the condenser and choke characteristics do not intersect.

In the case in point the high-tension winding and lead A (Fig. 1) of the transformer had appreciable capacitance to the transformer tank, which was permanently earthed. With terminal C earthed through the choke this self-capacitance is in effect lumped across the terminals A, B, and is therefore in series with the choke and the e.m.f. of the transformer. When the earth is made at C instead of at B the capacitance is in parallel with the e.m.f. and no jumps are to be expected. This explanation of the phenomenon was completely substantiated by measurement of all the relevant quantities. It is rather remark-

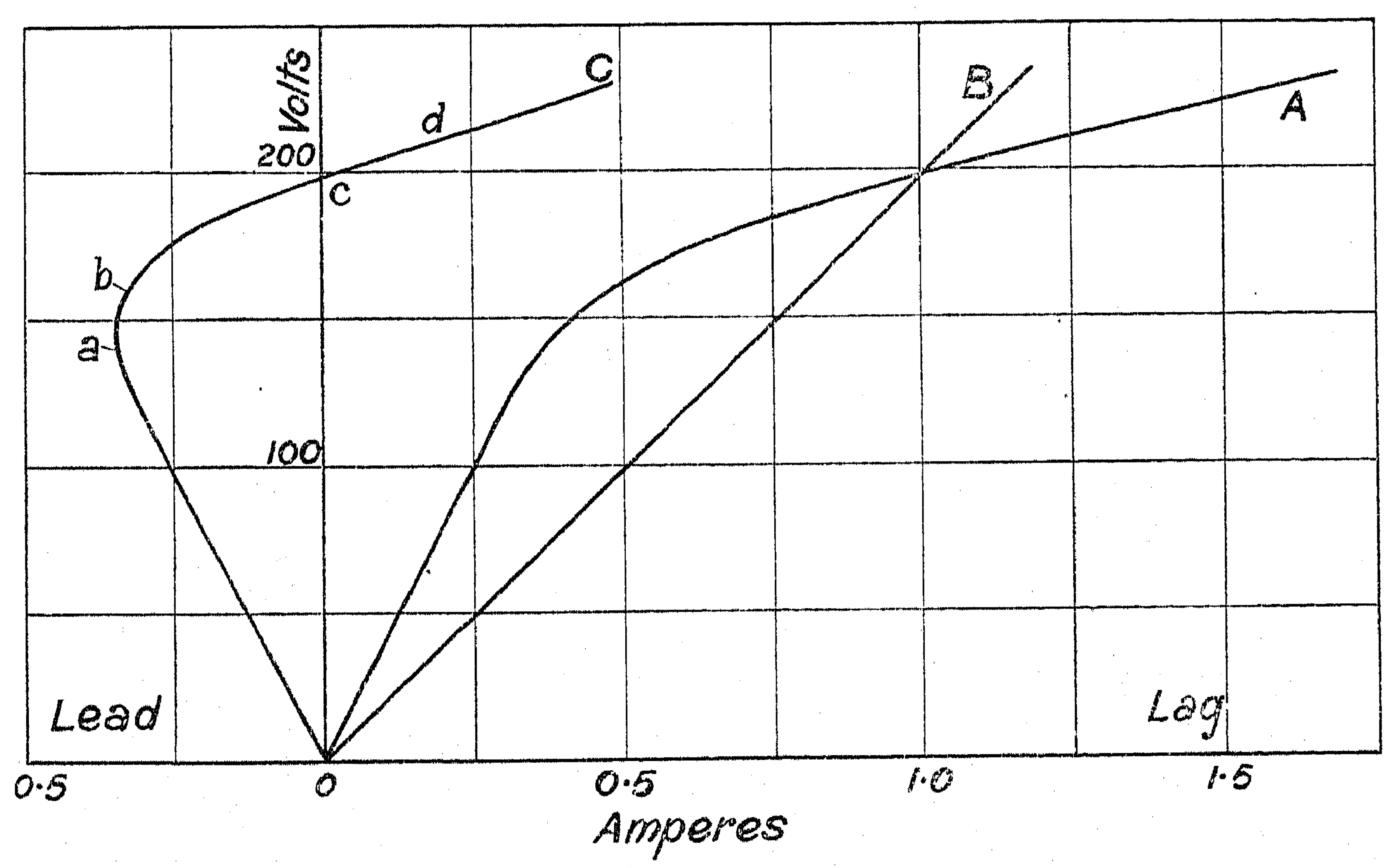


Fig. 5

able that the effect of such a minor change in connections should be so great.

CASE 2

The equipment consisted of a small testing transformer, the primary voltage of which was varied by means of a simple series sliding resistance. When the equipment was carrying an unusually large capacitance load a sudden jump of voltage occurred as the resistance was gradually cut out.

In Fig. 5, curve A is the transformer magnetizing current, curve B the reversed condenser charging current, and curve C the resultant fundamental-frequency zero-power-factor current I drawn through the series resistance R from the supply. If the transformer losses are neglected, so that the voltage V across the transformer terminals leads or lags on I by 90°, we have, for the supply voltage E, the equation

$$E_S^2 = V^2 + (RI)^2$$

whence
$$R = \frac{\sqrt{(E_S^2 - V^2)}}{I}$$

V and I are related by the curve C; a curve of R as a function of V calculated from this equation with $E_S = 230$ volts is plotted in Fig. 6. As the series resistance is decreased the primary voltage will rise; after the point a has been reached an increase of V is accompanied by a decrease of I; at the resonance point $V = 198$, I is zero, and there is therefore no drop in the series resistance. Instability therefore ensues soon after the point a has been reached, the voltage jumping suddenly from the value represented by b to that represented by d; a similar jump will occur in the reverse direction, say from c to e.

Actually matters are not quite as simple as is suggested by these diagrams, because even at the resonance point the transformer still draws loss current and harmonic magnetizing current from the supply. The latter has no effect except to distort the wave-form, but the loss current eliminates the infinite point from the R/V curve, which takes the form $abcd$. If the loss current is large enough, c may lie below b, in which case no jump will

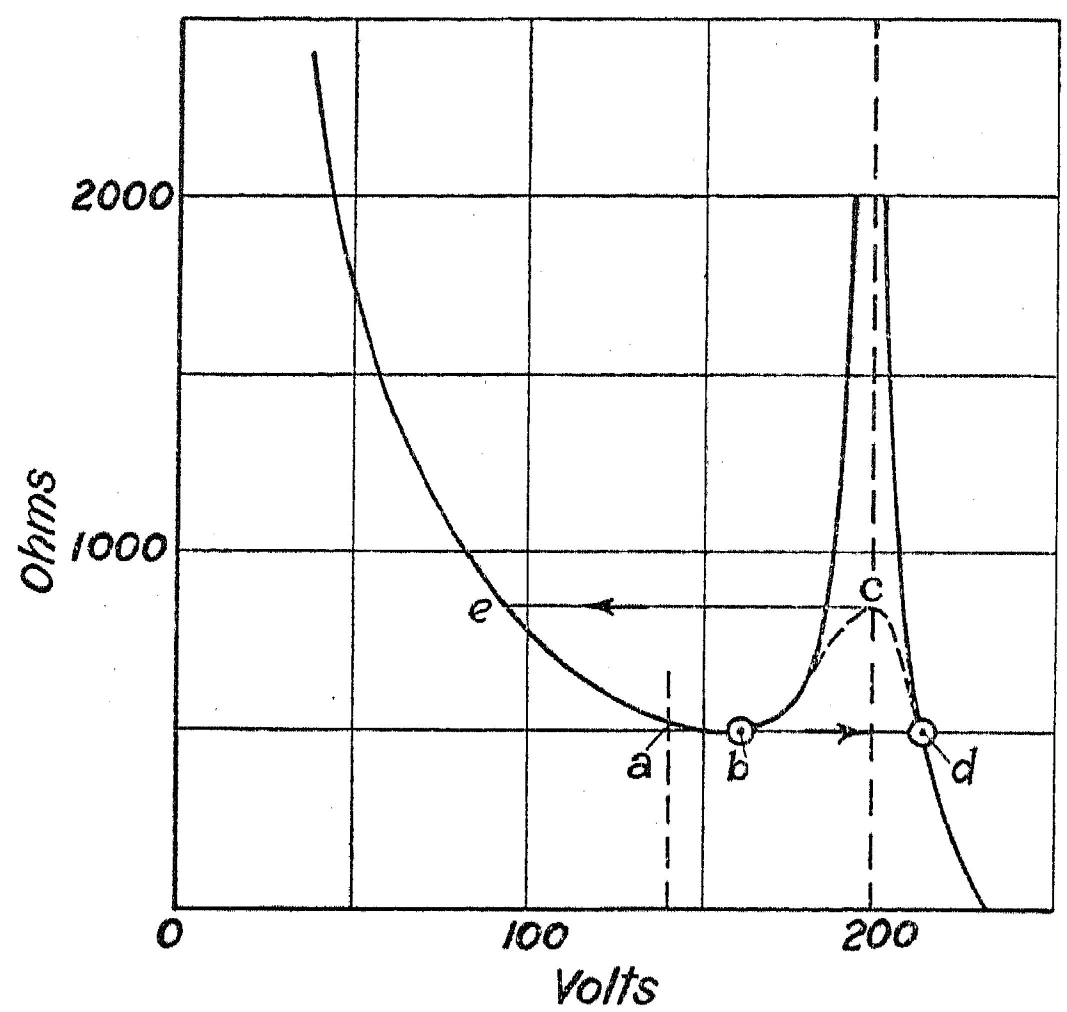


Fig. 6

occur. This suggests that the instability can be eliminated by connecting a suitable resistance in parallel with the primary winding, and tests show that this prediction is correct. A potentiometer resistance control is therefore unlikely to give trouble.

The author is indebted to Mr. A. K. Nuttall, M.A., for directing his attention to the first of the phenomena described, and to the Metropolitan-Vickers Electrical Co., Ltd., for permission to publish this paper.

THE POST OFFICE SPEAKING CLOCK

By E. A. SPEIGHT, Ph.D., and O. W. GILL.

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SUMMARY

The speaking clock, introduced recently by the General Post Office, provides an accurate time service which is continuously available to telephone subscribers in the London area. A subscriber connected to an automatic exchange on dialling the code T-I-M, or a subscriber connected to a manual exchange on asking for "Time," is routed to the clock and hears the time announced every 10 seconds. Each announcement is followed by three audio-frequency "pips," the last of which indicates within $\pm 0 \cdot 1$ sec. the exact time spoken.

The announcements are made by photo-electrically reproducing words or phrases, which are selected in the correct sequence from recordings made photographically on four glass discs. The mechanism for rotating the discs, for building up the announcement, and for changing from one announcement to another, is driven by a low-speed synchronous motor. The frequency of the a.c. supply to this motor is directly controlled by a seconds-beating free pendulum. Every hour the clock is checked automatically against a signal transmitted from Greenwich Observatory, and any small error is corrected. Should the error exceed the prescribed limits the service is transferred to a duplicate standby clock.

Facilities are provided to connect up to 100 simultaneous calls to the installation.

INTRODUCTION

Modern conditions of living have created a widespread desire that barely existed only a comparatively few years ago for accurate knowledge of the time. It is therefore of interest to trace briefly the development of the various time services available in this country up to the introduction of the latest innovation—the speaking clock.

Up to the beginning of the 19th century the time in most towns was taken from public clocks of some kind. There is no doubt that disagreement between these was the rule rather than the exception. This was a serious obstacle to the smooth working of the postal services and led to the practice, on mail coaches and trains, of carrying chronometers to synchronize local post-office clocks with a standard clock in London.

Following the introduction of the electric telegraph, electromechanical devices were tried for automatic synchronization of local clocks by means of telegraphed signals.

A parallel development was the synchronization of the London Post Office clocks with the standard mean time clock of the Royal Observatory at Greenwich. Experiments on these lines began about 1850. By 1874, i.e. a few years after the Government acquired the telegraph system, distribution of the 10.00 a.m. Greenwich signal over 60 different lines had been accomplished.

Introduced in 1927, the logical development of this service is the very accurate International Time Signal transmitted from Rugby radio station at 10.00 and 18.00 G.M.T. daily.

From the public point of view these services have the disadvantage of not being readily available where most needed, namely in the home. This need was partially satisfied when a telephone subscriber could learn the "Time by the exchange clock" on asking his local operator. This service was available on demand but was never claimed to be highly accurate. Its popularity, however, may be judged from the steady increase in the use made of it. In the London area, for example, about 100 000 inquiries per month were received.

The well-known "six pips" transmitted by the B.B.C. are more accurate, but are available only at certain times.

A different kind of service is that now available by the use of synchronous-motor clocks running on frequency-controlled mains. The use of these clocks, although steadily increasing, is far from universal at present.

A critical consideration of existing services therefore showed that there was a considerable demand for the service which is now provided by the speaking clock. This was confirmed by the success of similar services in certain Continental towns. For example, 10 000–12 000 calls are made daily to the speaking clock which was installed in Paris early in 1933.

REQUIREMENTS OF THE SERVICE

Admitting the need for the new service, the conditions which it should meet may be considered.

In the first place, the accuracy of the announcements should not suffer from adverse criticism when compared with existing public services. It was therefore decided that the time announced by the clock should not be more than $\pm 0 \cdot 1$ sec. in error. This accuracy is hardly astronomical, but is believed to satisfy the needs of the majority of probable users of the service.

To reduce the quantity of apparatus required for distributing the service without diminishing its availability, the announcements should be made frequently. This condition is met by providing six complete announcements per minute.

In deciding upon the wording of the announcement prior consideration was given to simplicity, clarity, and naturalness. Secondly, the wording chosen should not cause avoidable engineering complications in its reproduction. For example, certain short pauses are necessary for switching purposes. It is desirable that these should occur naturally, as if an actual person were speaking. The form finally adopted is illustrated by the following four typical announcements. (1) At an exact hour: "At the third stroke it will be ten o'clock precisely." (2) At (say) 10 seconds past the hour: "At the

third stroke it will be ten o'clock and ten seconds." (3) At an exact minute past the hour: "At the third stroke it will be ten, twenty-five precisely." (4) At other intermediate times: "At the third stroke it will be ten, twenty-five and twenty seconds."

Each phrase is followed by three 1 000-cycle "pips" of 0·1-sec. duration, the last of which indicates the time as announced.

DESIGN OF SOUND RECORDS

Choice of Recording System

Most recording systems may be classified as mechanical, magnetic, or photographic in principle. The first is typified by the gramophone record. This is compact and cheap to produce, but has a fairly high noise level which increases steadily with the fairly rapid wear occurring in reproduction. Gramophone records have, in fact, been used for a speaking clock installed in India, but it was found necessary to replace them every 1 or 2 days.

Magnetic sound recording is exemplified by the steel-tape record. Owing to the high velocity of the tape relative to the reproducing head a considerable length of tape is required for a given playing time. The initial quality of the reproduced sound is good and the noise level low, but experience shows that both quality and volume deteriorate noticeably after about 40 playings.

The photographic system involves a rather more complicated recording technique than the other two systems, but this is more than outweighed by its advantages for the present purpose. The initial quality of reproduction is good and the noise level low. Moreover, the form of record actually used in the clock is not subjected to any mechanical wear, and is, therefore, for all practical purposes permanent.

Form of Record

The form and basis material of the records depend not only upon acoustic requirements, but also upon the mechanical features of the reproducing device.

Sound track printed on paper strip, wound on an opaque drum and reproduced by reflected light, has been used in certain Continental systems.* At the outset of this investigation little was known of the behaviour of such records in service. It was felt, however, that dust and surface scattering of light and distortion of the record due to changes in atmospheric humidity might cause deterioration of the speech quality. A transparent record reproduced by transmitted light was therefore preferred.

Another Continental speaking clock does in fact use flat discs of celluloid film carrying circular sound tracks and sandwiched between glass plates.† This construction, although probably superior to paper strip, is not entirely free from objection on grounds of instability. Normal cinema film is open to similar objections and, further, is difficult to employ in a manner which will avoid mechanical wear.

For these reasons, and on account of the fact that suitable recording technique had been evolved, it was decided to use glass as the basis material for the records.

* *Révue Générale de l'Électricité*, 1932, vol. 32, p. 315.
† *Ericsson Review*, 1934, vol. 2, p. 85.

Dimensions and Arrangement of Sound Discs

Good reproduction of frequencies up to at least 10 000 cycles per sec. can be obtained from ordinary sound film travelling at the normal speed of 18 in. per sec. relative to the reproducing head. At this speed approximately 9 ft. of sound track would be required for the spoken part of the announcement, which lasts about 6 sec. To record separately each different announcement in the 12-hour period would therefore require nearly 8 miles of sound track. This is obviously impracticable. Furthermore, it would be almost a physical impossibility for any speaker to maintain uniformity of volume, intonation, and rate of speaking for the recording time required, and the cost of such lengthy records would be prohibitive.

It is necessary, therefore, to divide the announcement into words or short phrases and, by switching from one record to another, to make each serve for as many announcements as possible. For example, the same record of "At the third stroke" is used for every announcement. The subdivision must be such that these switching operations introduce no unnatural pauses.

At this stage it appeared that the best form of record was that of concentric circular tracks on flat glass discs, reproduced by rotating the discs in front of stationary optical systems. The overall diameter of the discs was fixed at 12 in. since it would be difficult to obtain larger sheets of glass which would be truly plane and remain so after processing. Further, any inaccuracy in the mounting of the discs on the shaft or inherent in the discs would be more pronounced at larger diameters and would lead to loss of articulation by defocusing the optical system. The diameter of the outermost sound track is 11 in. In order to accommodate as many tracks per disc as possible without unduly restricting the speech output, the radial width of the tracks was fixed at 2 mm.

By trial it was found that the time required for speaking the longest of the "minutes" words was 0·9 sec. To allow for switching, a speed of 1 revolution per sec. was chosen. Without loss of quality in reproduction it would therefore be possible for the length of the innermost track to be 18 in. This just permitted the use of two discs only for the 60 "minutes" records.

It is unnecessary to discuss in detail the reasons for the allocation of particular phrases to particular discs, and a brief description of these in their final form will suffice.

Although the complete announcement is divided into six parts, four discs only are required since two of the discs each perform two functions. Thus, one disc carries the following records. Outermost track: "At the third stroke." Six inner tracks: "Precisely," "and ten seconds," etc. The time taken to speak the longest of these is only 1·7 sec. To simplify the mechanical arrangements, however, a speed of 1 revolution in 2 sec. was chosen. Another disc serves for the "hours" portion of the announcement, and carries the records: "it will be one," "it will be two," etc. The actual sequence of the tracks on the disc differs, however, from the simple numerical order, since this would entail the necessity for the reproducing system to make a large movement in returning from "it will be twelve" to "it will be one." The order used is shown in Table 1.

In this order the passage from one hour to the next normally involves a movement of two track-widths, i.e.

4 mm., but at each end of the half-cycle of operations a single 2-mm. movement is required. This principle is applied to each disc and greatly simplifies the mechanical design.

In general, there is no fundamental reason for the choice of any particular record as the outermost or as the innermost track. In this case, however, an important point is that, with the arrangement chosen, should the 24-hour time system be required later, the change could be accomplished without need for further recordings.

The low speed of this disc causes a slight attenuation of the highest speech frequencies of the inner tracks but, even in the worst case, the loss is negligible up to 6 000 cycles per sec.

The next disc is used for the " even minutes " records, the place of " zero minutes " being taken by the words " o'clock."

The remaining disc carries the " odd minutes " records as well as a short recording, lasting 0·1 sec., of a 1 000-cycle note. The three " pips " are obtained by reproducing this note three times in succession.

the film is firmly clamped to the periphery of an aluminium drum so that the sound track projects beyond the edge. After some practice it became comparatively easy to match the spoken phrases closely to the standard phrase both in intonation and in duration. Similar means were adopted in recording the remainder of the words and phrases required.

The master disc negatives were made on flat glass plates, suitably sensitized. The plate was held in a mounting and rotated at constant speed about a central axis at right angles to the face. The slit of a sound-recording oscillograph was focused as a short radial line on the plate. Arrangements were made to adjust the diameter of the track so formed exactly to a predetermined figure. Each selected film record was reproduced in turn by means of the drum apparatus just described, and the output from the amplifier of this apparatus was fed to the oscillograph element. By this means the word or phrase recorded on the film was re-recorded on the plate. Great care was necessary in this process to ensure that the speeds of the drum and

Table 1

ORDER OF TRACKS ON " HOURS " DISC

Track Number	Phrase	Track Number	Phrase	Track Number	Phrase
(1) (outside)	" It will be 6 "	(10)	" It will be 11 "	(18)	" It will be 15 "
(2)	" It will be 7 "	(11)	" It will be 1 "	(19)	" It will be 22 "
(3)	" It will be 5 "	(12)	" It will be 12 "	(20)	" It will be 16 "
(4)	" It will be 8 "	(13)	" It will be zero "	(21)	" It will be 21 "
(5)	" It will be 4 "	(14)	" It will be 13 "	(22)	" It will be 17 "
(6)	" It will be 9 "	(15)	" It will be 24 "	(23)	" It will be 20 "
(7)	" It will be 3 "	(16)	" It will be 14 "	(24)	" It will be 18 "
(8)	" It will be 10 "	(17)	" It will be 23 "	(inside) (25)	" It will be 19 "
(9)	" It will be 2 "				

Recording Process

To build up the complete announcement satisfactorily requires close control of the duration of each word and accurate placing of each record on the disc. The early trials soon showed that it was not possible to produce satisfactory discs by direct recording. The speech required was therefore first recorded on standard sound film and subsequently transferred to the discs.

A difficulty experienced by the speaker in accurately controlling the duration of each word and in maintaining uniform intonation was overcome in the following manner. From many repetitions a satisfactory film recording of " At the third stroke " was selected. This was reproduced from a loud-speaker in the recording studio and, after each playing, the announcer spoke one of the phrases " it will be one," " it will be two," etc. Since many repetitions of the standard phrase were required during both rehearsal and recording, a special form of reproducer was used to avoid wear of the film. The apparatus used was developed by the authors some time previously for the purpose of substituting spoken phrases, e.g. " Line engaged," for certain of the signalling tones used in ordinary telephony. In this apparatus

of the plate carrier were correctly related and that the phrases were recorded so as to begin or end in the correct relative positions on the plate. This is necessary in order to avoid awkward pauses or overlapping when the record is reproduced by the clock.

Early practical trials made with announcements built up from strips of film showed that it was particularly necessary for the interval between the end of the " hours " phrase and the beginning of the " minutes " to be constant and fairly short. For this reason all the former end and all the latter begin on radial lines on the respective discs. The relative positions of the two sets of tracks on the dual-purpose discs were determined by the positions, in time, of the various words in the announcement, due regard being paid to the location of the two reproducing systems associated with each of these particular discs.

In all cases the sound tracks are of the so-called " variable area " type.

Simultaneously with the speech currents fed to the recording oscillograph a d.c. bias was automatically applied so that the width of the sound track tapered to zero both at the beginning and at the end. A black area was thus produced on the positive prints, which

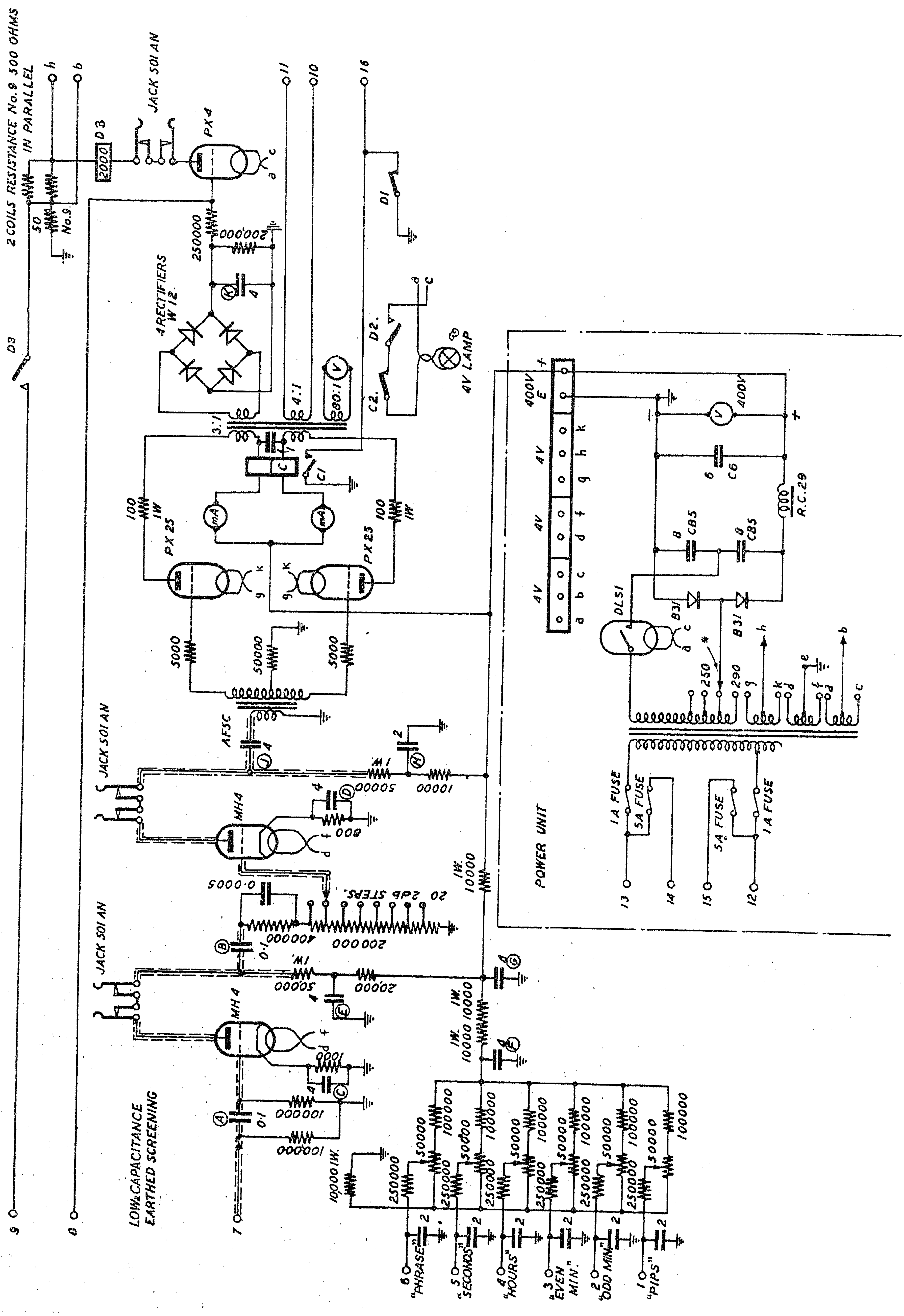

Fig. 1.—Speech amplifier.
* Tapping selected to give 400 volts H.T.

avoids noise due to shuttering, whilst the gradual build-up and die-away avoid noise as the track enters and leaves the reproducing beam of light.

REPRODUCTION OF THE SPEECH

The method of speech reproduction follows standard practice. The exciter lamp can be rotated slightly in its holder, which is also adjustable for height in order to bring the (horizontal) filament at right angles to and in the same plane as the optical axis. The optical system itself is of normal design and is provided with adjustments for focusing, for setting the length of the slit, and for setting the slit radial to and centrally over the sound track. The photocell is contained within a tubular shield which is perforated so as just to pass the reproducing beam of light. With this arrangement no trouble due to stray light has been experienced, in spite of the use of alternating current for the room lighting.

The circuit of the speech amplifier (Fig. 1) shows little departure from standard practice. For simplicity, the cathodes of all six photocells are connected together and to terminal 7 of the amplifier. The photocells used are of the gasfilled caesium type. Since individual cells may differ considerably in sensitivity, the outputs are

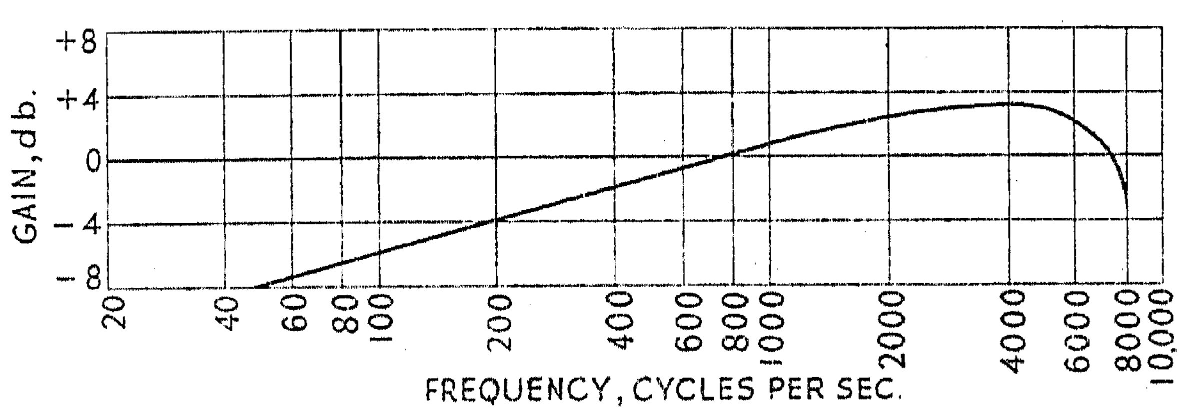

Fig. 2.—Frequency characteristic of speech amplifier.

equalized by the use of variable potentiometers controlling the voltage applied to the anode of each cell. The overall gain is controlled by means of the variable potentiometer between the first and second stages.

Even with the use of special low-capacitance screened cable for the photocell leads, some loss of the upper audio frequencies occurs. The input impedance of the amplifier is therefore kept low and a tone-correcting circuit is included between the first and second stages. The frequency characteristic of the amplifier with photocells connected is shown in Fig. 2.

The connecting cables between the speech amplifier and the distributing relay sets are of considerable length. To avoid loss of the higher speech frequencies due to the capacitance of the leads, and loss of volume due to their resistance, the main secondary winding of the speech-output transformer in the amplifier gives a step-down ratio of 4 : 1, which, with the output valves used, requires a matching load of 400 ohms. A second output transformer, mounted on the relay set rack, gives a further step-down of 20 : 1 and, in conjunction with a 1-ohm resistance connected directly across the secondary winding, provides the correct load.

The impedance of the shortest subscriber's line is not much less than 600 ohms, so that even with 100 lines simultaneously connected the total output load impedance falls only to about 0·9 ohm. Practical listening trials showed no detectable difference in volume whether 1 or 100 subscribers were connected. As a check on the speech voltage applied to the relay sets, a rectifier-type voltmeter is joined across a tertiary winding on the main output transformer.

ALARMS

To safeguard the continuity of the service an alarm is necessary should the speech output fall below a predetermined level. For this purpose speech currents derived from a fourth winding on the main output transformer are rectified by a bridge-connected metal rectifier, and charge the condenser K (Fig. 1). The circuit values are such that, in consequence, the associated valve (PX4) operates at substantially zero bias. Anode current flows, holding relay D in the operated condition. Should the speech output fall, negative bias is applied to the valve by a suitable resistance network, whereupon the anode current falls and relay D drops out. If the valve itself fails, D again drops out. Between the end of the "seconds" phrase and the beginning of the next announcement only the "pips" occur, and these are too short to maintain the charge on the condenser K. To hold the relay operated during this period the grid of the valve is brought to zero bias by means of contacts closed by a cam—the "alarm suppressor" cam—on the clock mechanism and connected to terminals 8 and 9. A contact D3 of relay D is included in this circuit so that the relay cannot be operated initially, or brought in again after a speech failure, except by the correct speech output. Unless relay D is operated, terminal 16 is earthed via contact D1 and, as will be seen later, an alarm bell is sounded and subscribers cannot be connected to the amplifier.

Failure of one of the early valves would be indicated in this way, but failure of one only of the output valves would not necessarily be shown, although the reproduced speech would become distorted. The separate anode-feeds to the output valves are therefore taken through the differentially wound relay C. If the output stage becomes unbalanced, this relay operates and earths terminal 16. To prevent loss of the higher speech frequencies the windings of this relay are shunted by a condenser.

To expedite the diagnosis and clearing of possible faults, various meters and milliammeter jacks are provided in the anode circuits, and a pilot lamp glows as long as a satisfactory output is being given.

The shortest-lived components in the reproducing systems are the exciter lamps, failure of one of which would cause an incomplete sentence to be sent out. To obviate this the filaments are series-connected, so that a partial failure is impossible. The lamps are rated at 10 volts but, to increase their life and to reduce the possibility of hum, the six are run from a 50-volt a.c. supply given by a transformer on the clock-mechanism base. Each lamp is shunted by a 50-volt low-power switchboard lamp which glows if the corresponding exciter lamp fails.

THE CLOCK MECHANISM

In contrast to the electrical units of the installation where some latitude in adjustment is, in many cases, permissible, the efficiency of the installation as a whole

depends upon a high degree of precision in the construction and operation of the mechanical units. In general, also, any fault which may develop in a mechanism is costlier and more difficult to remedy than an electrical fault. In the first place, therefore, accuracy and reliability were the principal aims. To this end the mechanical parts are as few as possible in number and were designed with a large margin of safety.

Maintenance of efficient operation needs only a minimum of attention over long periods, and the general layout permits ready replacement or adjustment of any of the few parts which may conceivably become defective in service.

The main functions which have to be performed by the mechanism are determined by the manner in which the announcements are made, on the one hand, and by the necessity for accurate timekeeping on the other. These functions will now be considered in greater detail.

Rotation of the Discs

Since the pip signal which indicates the exact time is recorded on, and reproduced from, the "odd minutes" disc, the speed of this and hence of all the discs must be accurately controlled. Further, for good speech reproduction the speed must be uniform throughout each revolution. As will be seen later, a special motor running at 60 r.p.m. has been developed for this purpose. This motor is shown at (1) in Fig. 3, which depicts the general layout of the clock mechanism.

Since the "odd" and "even" minutes discs—2 and 3 respectively—also rotate at 60 r.p.m., a direct drive is used. The "hours" and "seconds" discs—4 and 5 respectively—rotate on a separate shaft coaxially with the "minutes" discs, but a 2 : 1 reduction gear (6) is interposed to give the speed required—30 r.p.m. Helical gears of fine pitch are used, to avoid "flutter" due to backlash. Lubrication is by means of oil into which the countershaft gears dip. It was found necessary to devise a special form of oil-retaining washer to prevent leakage past the main bearings. Ball bearings are used throughout the mechanism to reduce friction.

The main bearing housings and gearbox are split along a horizontal plane through the axis of the main shafts to facilitate removal of the latter, if necessary.

Smooth running and maintenance of accurate focusing of the discs with absence of whip or vibration are essential to good sound-reproduction. The main shafts are therefore made of 1 in. diameter precision-ground mild steel. The discs themselves are mounted on flanged gunmetal hubs. The tapered ends of the hubs are split and contracted on to the shaft by means of nuts. Rings of blotting paper are inserted between the sides of the discs and the flanges of the hubs to improve the grip and avoid breakage. The central holes drilled in the discs are slightly larger than the central portions of the hubs to allow the discs to be accurately centred, and lines are scribed on the shafts, hubs, and discs to facilitate correct reassembly should the necessity arise for any replacement.

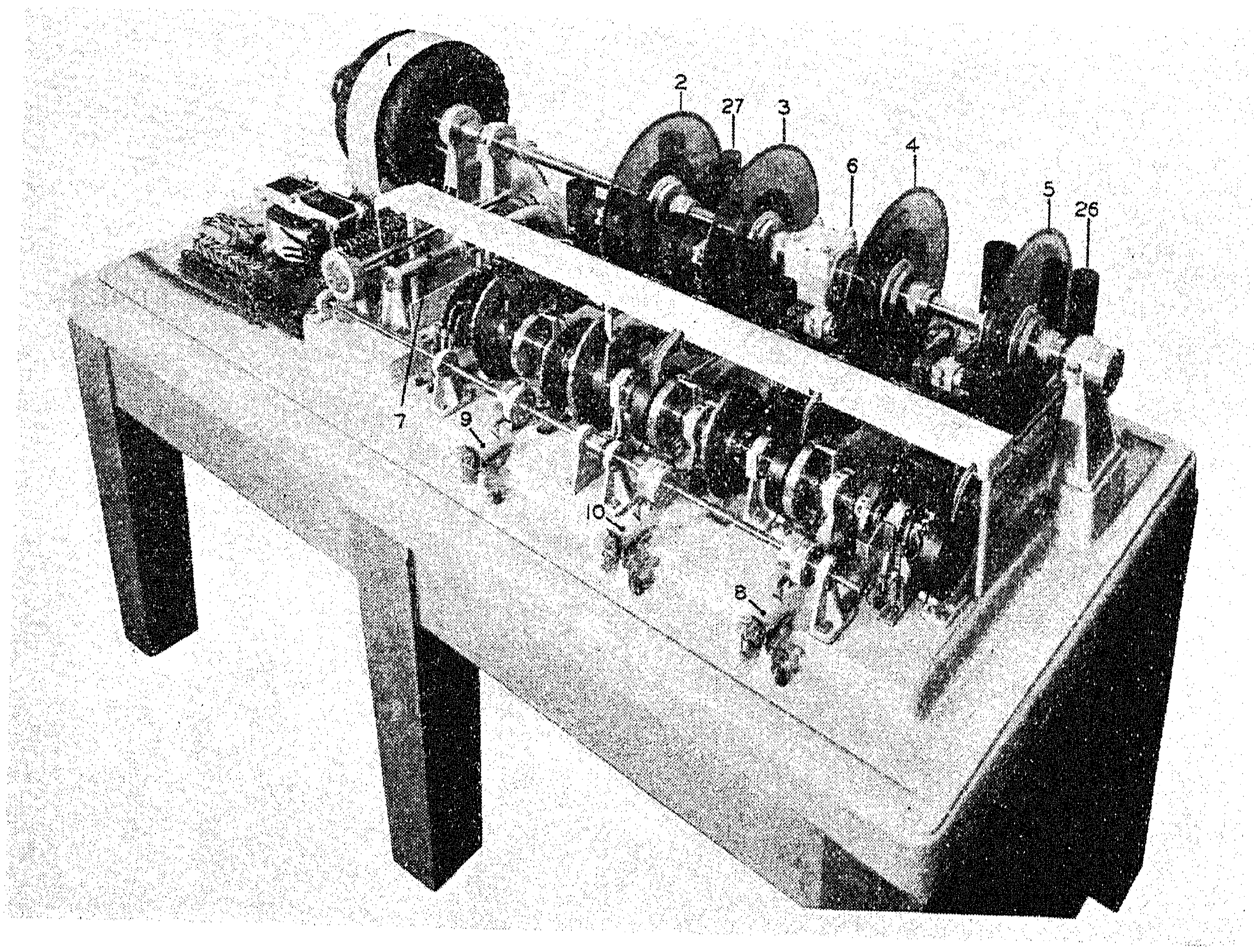

Fig. 3.—Clock mechanism.

Building up the Announcement

From the foregoing it is apparent that the discs are rotating and the exciter lamps are energized at all times. Some form of switching is therefore necessary in order

that speech shall be reproduced from only one disc at a time and in the correct order for building up the proper announcement. Since the first valve of the amplifier is common to all the photocells, such switching must occur before this valve is reached. In view of the high gain of the speech amplifier no attempt was made to devise a switching device for the photocell circuits. Switching the exciter lamps would necessitate the use of special heavy-current contacts and, further, would not be completely successful owing to the appreciable time of heating-up and cooling-down of the filaments.

For these reasons it was decided to perform the switching by optical means. This was accomplished by the use of electromagnetically-operated shutters interposed between the optical systems and the sound discs. These shutters normally prevent the passage of the beam of light to the disc, and no output is produced by the corresponding photocell. The announcement is built up by causing the discs to " speak " in turn by opening the corresponding shutters in the correct sequence. This is done by means of a series of contacts operated by cams which are rotated by means of a 10 : 1 reduction gear from the main shaft.

The manufacture of the cams had to be undertaken before the preparation of the discs was completed. When the mechanism was first put under test it was found necessary slightly to alter the relative positions of certain words in the announcement in order to produce a natural effect. This was, of course, done by slight alterations in the angular relationships of the various discs on their shafts, and the necessity for it was foreseen in the early stages of the design. It was therefore decided to make the individual cams adjustable so that the shutters could be set to open just prior to the commencement of the sound tracks and close just after the end of these. In this way noise is avoided by opening and closing the shutters when the black area of the disc lies before the optical system. (For the reproduction of the " pips " the track passes the optical system three times, and the associated shutter therefore remains open for just over two revolutions of the main disc shaft.) The necessary adjustment is provided by using split cams the two halves of which can be rotated separately through small arcs to give the setting required. These cams are made of bakelite clamped between the faces of flanged steel bushes keyed to the camshaft.

The blade of the shutter is so shaped that its movement varies as smoothly as possible the amount of light passing, in order to reduce still further any remaining possibility of " clicks " being caused by the operation. The magnet system consists of a small soft-iron armature carrying the shutter blade, suspended on hardened-steel pivots between the poles of an electromagnet. The shutter is normally held in the closed position by a light spring with the armature displaced angularly in relation to the axis of the pole-pieces. When the magnet is energized the armature is drawn more nearly into the magnetic axis, thereby opening the shutter. The travel of the shutter blade—about $\frac{1}{4}$ in.—is regulated by suitable fixed stops. To avoid the production of noise in the speech circuits it was found necessary to shunt the contacts controlling the switching operations by suitable resistance-condenser spark-quench circuits.

Change from One Announcement to the Next

Simply expressed, the change from one announcement to the next merely involves moving one or more optical systems so as to reproduce different sound tracks. In actual fact, however, the evolution of a truly satisfactory design for this vital part of the mechanism involved many major difficulties. This will be apparent from a consideration of the more important requirements to be fulfilled:—

First, the plane of movement of the optical system must be accurately parallel to the face of the disc to avoid imperfect focusing, with consequent loss in articulation.

Secondly, the extent of each movement of the optical system must be exact since there is no radial spacing between adjacent sound tracks other than that which arises from the fact that the maximum modulation of the track-width is 80 per cent.

Thirdly, the movement must take place smoothly in order to avoid undue mechanical wear yet must be completed during the short silent period between the end of one announcement and the beginning of the next.

In the final design each of the four movable optical units is mounted on a carriage which runs on ball-bearing rollers on two horizontal cross-guides situated respectively below and at right angles to the disc shafts. The carriages are moved by means of steel cams working on rollers mounted on the carriages. Contact between the cam faces and the followers is maintained by spring pressure.

This principle has the advantage that the steps of each cam are at equal angular spacings and the magnitude of each step is equal to the required movement of the optical system. Nevertheless, the manufacture of the cams presented several problems. The asymmetry of contour necessitated a considerable amount of hand work. To avoid the development of inaccuracy through wear the cams must be hardened, and freedom from distortion during hardening is therefore essential.

In the first stage of the shaping operation the blanks, consisting of Nitralloy steel, were " roughed-out " by hand to approximately the contour required, and then each step was milled to the correct radial distance from the centre. A radius was then milled leading from each step to the next, and the intermediate contour was finally blended in by hand filing and polishing. After hardening by the special treatment required by this material no measurable distortion could be detected.

In the case of the " minutes " cams the circle swept out by the cam proved to be inconveniently large. Accordingly, each of these cams is split into two portions using a smaller radial scale for the outer portion of the travel but keeping the lift of the steps the same. These cams can be seen in Fig. 4 (item 11). Each of the two " minutes " carriages is fitted with two separate followers, one of which runs on an eccentrically mounted spindle. This is necessary in order to match the followers accurately to the respective halves of the cam and give a smooth take-over. One of the additional followers is seen at (12). The two composite cams are mounted on a single camshaft so that the central radii of the steps of one lie midway between the steps of the other. The 60 positions required to cover the minutes are thus

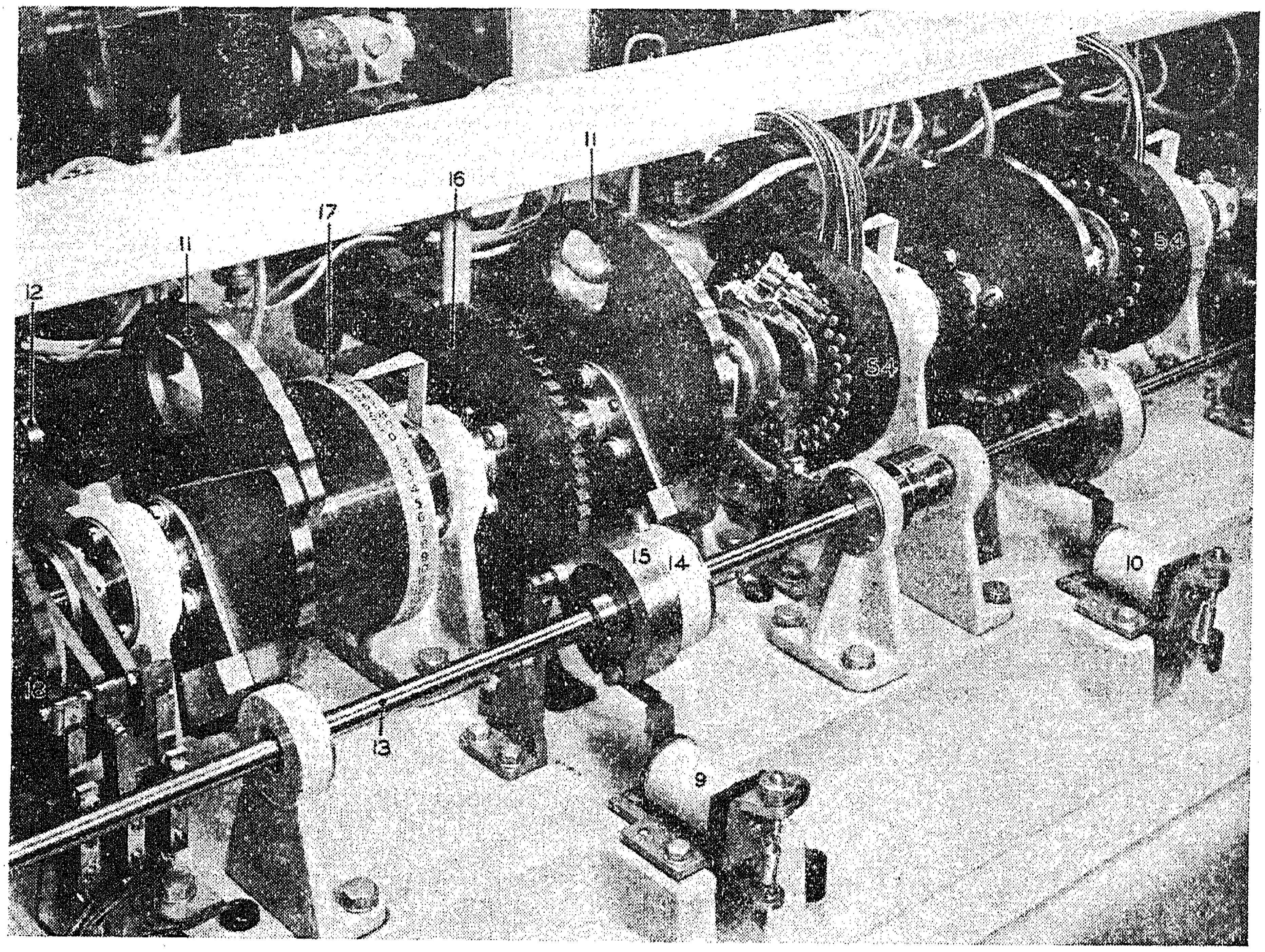

Fig. 4.—" Minutes " and " hours " camshafts.

obtained by the use of 30 steps only on each complete double cam.

The method of imparting the correct angular movement to the " minutes " cams can also be seen in Fig. 4. The shaft (13) is driven continuously at 60 r.p.m. by skew gearing from the main shaft. Mounted freely on this shaft is an eccentric (14), the sheave of which is integral with a special clutch (15). A connecting rod couples the strap of the eccentric to a swinging arm, which is freely mounted on the camshaft. A pawl carried on this arm engages with a 60-tooth ratchet wheel (16) which is pinned to the camshaft, and the throw of the eccentric is such that, when the clutch makes one complete revolution, this wheel advances one tooth and the cams move the carriages the appropriate distance. The time of movement is $\frac{1}{2}$ sec., which is slow enough to avoid damage due to rebound.

A light aluminium drum (17), suitably engraved and pinned to the camshaft, in conjunction with a fixed pointer, indicates visually the track being reproduced at each setting of the cams. The bakelite cam (18) operates a change-over contact which permits the operation of either the " odd minutes " or the " even minutes " shutter according to the setting at any instant.

The clutch (15), which turns the eccentric sheave through exactly one revolution as required, is shown more clearly in Fig. 5. Before incorporation in the final design a sample unit was subjected to a severe accelerated life test in the laboratory and found to function reliably. The main body of the clutch is freely mounted on the shaft (13), to which is pinned the ratchet wheel (19). The pawl (20) carried on the body of the clutch is normally held out of engagement with the ratchet wheel by the armature (21) of the electromagnet (9). When a momentary current is passed through the coil the armature is withdrawn from the projecting end of the pawl, which is then thrown by the spring (22) into engagement with the ratchet wheel. The whole assembly is thus

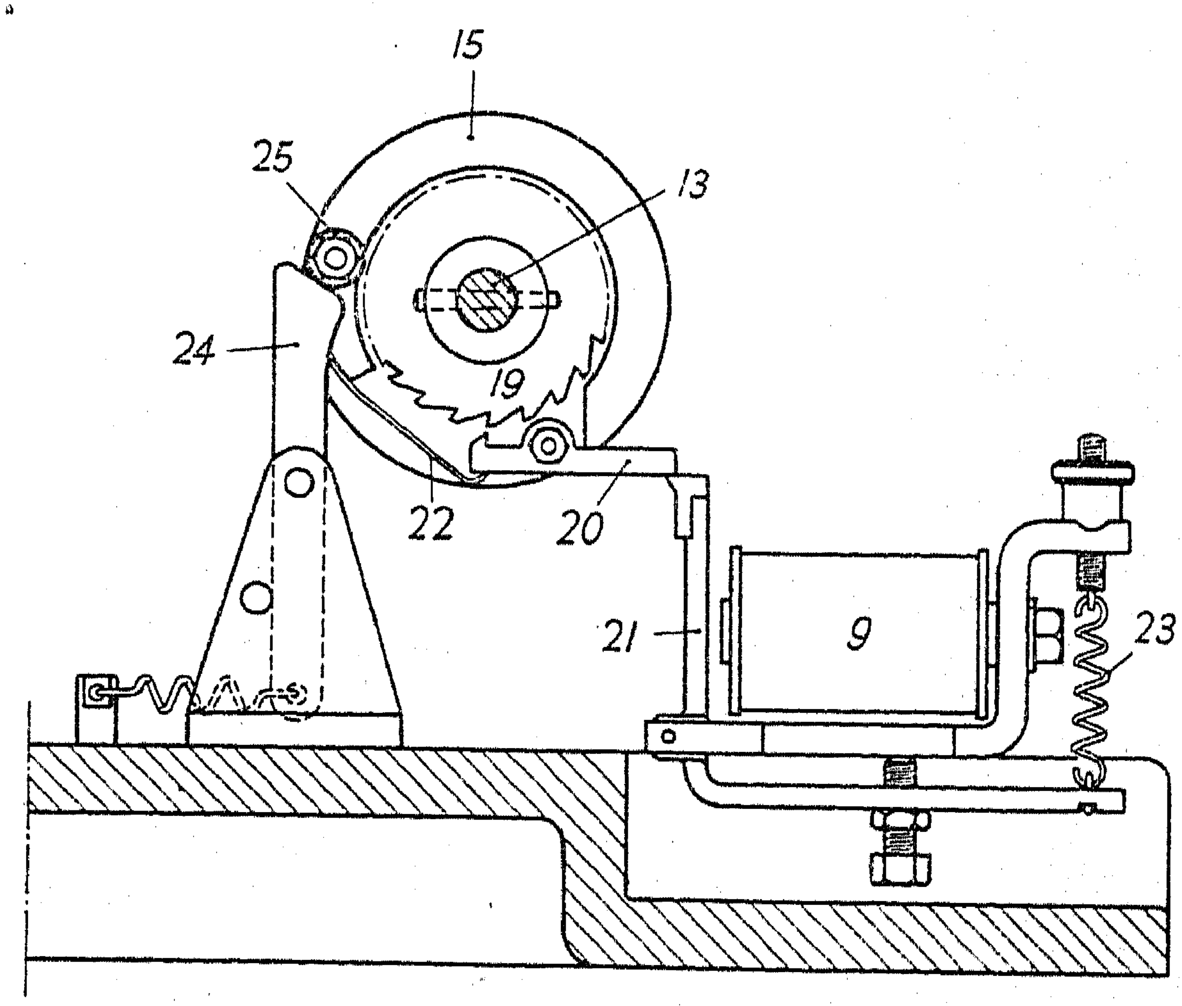

Fig. 5.—Clutch mechanism.

locked to, and rotates with, the shaft. When the current ceases the armature is returned to normal by the spring (23). On the completion of one revolution the projecting end of the pawl (20) strikes the armature, is thrown out of engagement with the ratchet wheel, and the whole assembly comes to rest. A spring-loaded lever (24) bear-

ing on a roller (25) holds the clutch in this position in readiness for the next operation.

The carriages associated with the "hours" and the "seconds" discs are moved similarly. The mechanism is seen in the foreground in Fig. 3. The sequence of operations of this mechanism is as follows: Immediately after the third pip of each announcement, a contact operated by a cam on the shaft (7) is momentarily closed. This energizes the electromagnet (8) and the "seconds" portion of the announcement is changed in the manner just described. When the "seconds" carriage moves into the position to reproduce "and 50 seconds," a contact associated with the "seconds" camshaft closes and connects the magnet (9) in parallel with (8). After the third pip of this particular announcement, both magnets are momentarily energized and simultaneously the "minutes" carriage moves to its next position and the "seconds" carriage to the "precisely" position. Similarly at "59 (minutes) and 50 seconds" the magnet (10) is paralleled with the other two. Following this announcement, the "hour" changes to the next, the "minutes" to "o'clock" and the "seconds" to "precisely," as before.

The introductory phrase "At the third stroke" and the three pip signals are common to all announcements. The optical systems used to reproduce these are shown at (26) and (27) respectively, Fig. 3.

The bedplate on which the whole of the mechanism is carried is a single casting in nickel-containing cast iron, 5 ft. 9 in. long by 2 ft. 9 in. wide. Machined surfaces are provided for all components, and all vital parts are dowelled in order to ensure accurate refitting in the event of removal being necessary. Suitable weathering periods were allowed to elapse before taking the final cuts in the machining operations, to avoid risk of distortion.

METHOD OF DRIVE

For a mechanism of this size and complexity the requirements of the method of drive are unusually stringent. It is obviously desirable to use one driving motor for the whole mechanism if possible. The power required to drive the discs only is small but the peak requirement, which occurs once per hour, i.e. when all three camshafts move simultaneously, is relatively large. An adequate margin of power above this peak is necessary and the whole rotating system must possess sufficient inertia to prevent noticeable speed fluctuations with change of load.

It has already been seen that the speed of rotation must be accurately controlled. Since the maximum error permissible is $\pm 0 \cdot 1$ sec., the gain or loss per hour, assuming hourly correction, should not exceed $0 \cdot 05$ sec. In round numbers the speed should be correct within about 1 part in 100 000. This necessitates some form of continuously-operating control, in spite of which, however, an error exceeding $0 \cdot 1$ sec. could ultimately accumulate. A periodical overriding check is therefore required to correct this error. This operation should be automatic, and the whole scheme should not need constant or skilled attention for its efficient working. In view of the novelty of the scheme ultimately used it is believed that a short account of the experiments leading up to its adoption may be of interest.

Methods Available

Greenwich Mean Time is naturally the standard against which the clock is compared. The periodical check therefore employs the signal transmitted exactly at each hour from the Observatory.

For the continuous control, however, various possible methods are available. One of the simplest would be to use a synchronous motor running on time-controlled a.c. mains for the main drive. At present, however, the required accuracy cannot be attained by this means and there is no simple way of providing an effective standby drive in the event of mains failure. Two other possibilities are a motor whose speed is under the control of an accurate tuning-fork, or a pendulum.

At the outset of these investigations little was known of the behaviour of low-frequency tuning-forks. A few experiments were actually carried out in which a 50-cycle fork was used to control the frequency generated by an inverter circuit using gasfilled relays, but it appeared doubtful whether the required frequency stability and reliability could be attained.

The properties of higher-frequency, e.g. 1 000-cycle, forks are better known and, with close temperature control, the required accuracy could undoubtedly be reached. It would be necessary to follow such a fork with a frequency divider or to use a very high-speed motor with a high-ratio reduction gear in order to obtain the low speed of the clock mechanism. The disadvantages of such schemes are apparent and, in view of the success attained in early experiments using a pendulum, further work on forks was abandoned.

PENDULUM SPEED CONTROL

Preliminary Investigation

For the early experiments on pendulum control a clock known as the Clock No. 36 was used. This is an inexpensive electric master clock widely used throughout the Post Office Engineering Department. It has a seconds-beating pendulum employing an invar rod. The swing of the pendulum is maintained by means of the well-known Hipp toggle contact and electromagnet. Normally, in addition to contacts closed every second, the pendulum operates count wheels closing further contacts at intervals of 6 and 30 sec. This mechanism was removed for the present investigation. The 1-sec. contacts were used to operate a secondary dial by the aid of which the daily rate of the pendulum was measured. It was found possible to maintain a rate of $\pm$ 1 sec. per day without difficulty. This is of the right order.

For the present purpose the hourly rate throughout the 24-hour period was of greater importance. This was measured in the following manner. The 1-sec. contact was removed and the length of the arc of swing measured with reduced energy input to the driving magnet so that the difference between maximum and minimum amplitude was small. A photographic transparency shaped as shown in Fig. 6 was mounted at the bottom of the pendulum. The image of a vertical narrow illuminated slit was focused centrally on the transparency when the latter was at rest. The base of the transparent area was equal to the arc of swing, and the shape was such that when the pendulum was swinging normally the amount

of light passing through the trace and falling on a photocell varied sinusoidally at 4 cycles per sec. (The transparency was prepared by photographic reduction from a drawing 10 times the linear dimensions of the trace required.) Despite the very low frequency it was found possible to amplify the output of the photocell by means of an amplifier of straightforward design. A small 2-pole synchronous motor was constructed which was driven at 4 revolutions per sec. by the a.c. output of the amplifier. The motor, with the aid of suitable gearing, operated contacts which selected and recorded one particular second in each hour as a deflection in the line traced by one pen of a syphon recorder. The other pen of the recorder recorded the signal transmitted from Greenwich Observatory at each hour. By simple measurement the rate of the experimental pendulum during each hour could readily be computed.

The results, over a period of some months, showed that this pendulum could be adjusted to run true to time with an error of $\pm 0{\cdot}05$ to $0{\cdot}1$ sec. per hour. This was nearly good enough.

The success of these experiments suggested that if the pendulum could be arranged to swing perfectly freely (in the horological sense of the word) by eliminating the Hipp escapement, still better timekeeping could be secured.

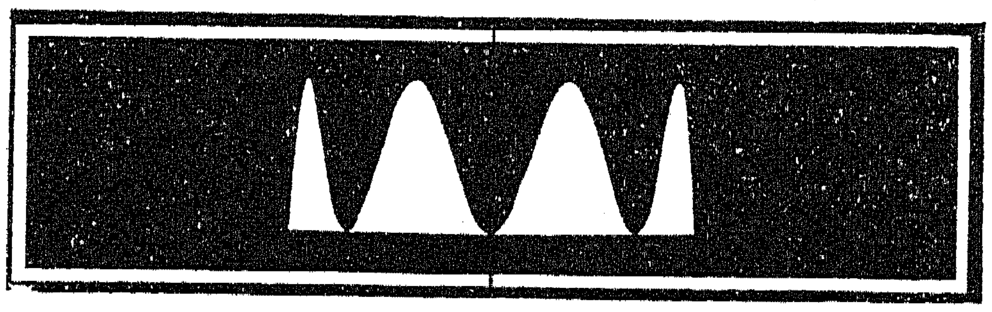

Fig. 6.—Four-cycle wave trace.

At this stage various ways of employing such a pendulum were examined in order to determine whether any further increase in accuracy could profitably be utilized. There are several known methods of employing a pendulum for the purpose of speed control. In most of these a d.c. motor is used which, in addition to driving some mechanism, operates contacts at regular intervals. By means of relays the operation of these contacts is compared with the operation of other contacts by the pendulum. The speed of the motor in relation to the time of swing of the pendulum is thus determined and corrections are made as required by automatic control of the field excitation.

There are several disadvantages of such schemes. The operation of contacts adversely affects the accuracy of the pendulum. These contacts are called upon to operate frequently and, at the last stage, to control appreciable power in an inductive circuit. Frequent maintenance attention would therefore probably be necessary, and difficulties were expected in avoiding the introduction of noise into the speech circuits. Appreciable variations of speed from moment to moment are inevitable although the mean speed over a period may be correct. There is a definite risk that this may cause noticeable changes in the pitch of the reproduced speech. Finally, the use of a relatively high-speed motor and gearing introduces maintenance problems which are largely absent in a purely low-speed mechanism.

For these reasons attention was concentrated on direct utilization of the 4-cycle current generated in the manner just described. The first problem was naturally that of securing efficient amplification at this low frequency. Resistance-capacitance intervalve couplings with a large enough time-constant are straightforward. Even transformer couplings are perfectly practicable if the windings are designed to have enough inductance. In this case, however, an alternative path for any direct current in the circuit must be provided in order to avoid saturation of the core. This last point is particularly important in the design of the output transformer, the windings of which must carry the mean direct current flowing in the valve anode circuits. This problem was solved by using cores of relatively large cross-section, and a balanced output stage in which these d.c. components cancelled out. Apart from these considerations the transformer design was carried out in the normal manner.

Convenience and the relatively large output power required made almost inevitable the choice of a.c. mains for the energy supply to the amplifier. The overall gain of the amplifier is very high and particular care was therefore necessary in order to prevent unwanted interaction. For the sake of their low impedance, mercury-vapour rectifying valves are used in the H.T. supply unit, and the actual circuit used incorporates the suggestions made by Dunham* to give good voltage regulation. Very thorough decoupling is used in the individual anode feeds. As a further precaution, the second stage of the 4-cycle photocell amplifier is connected in push-pull in order to reduce circulating alternating currents in the power unit. (As will be apparent later, the same result is incidentally achieved in the later stages of the final amplifier.) The first form of output stage employed two triodes in push-pull. Valves dissipating 75 watts at an anode voltage of 1 000 were used and delivered a 4-cycle output of 36 watts into the load.

This output was used to drive an experimental synchronous motor at 60 r.p.m. Since it was ultimately superseded, it is unnecessary to describe this motor in detail except to state that its measured characteristics were very close to the calculated figures and that its efficiency at full load was over 80 per cent. The mechanical power output was adequate, but the speed under load showed a slight periodic fluctuation due to the inherently pulsating nature of the torque produced. When the motor was used for driving a sound disc this speed fluctuation was manifest by a slight but detectable "wobble" in the reproduced speech. Although in this precise form the method of drive was not entirely satisfactory, the experience gained in its development suggested that complete success was probable if the scheme could be modified to polyphase working.

Development of 3-phase 4-cycle Drive

The basis of the design was the 3-phase sinusoidal oscillating circuit devised by Van der Pol.† As this circuit does not appear to be widely known, it may be considered briefly. The basic circuit is shown schematically in Fig. 7, item 49. [For the moment the transformer winding (50) may be ignored and the upper end of the resis-

* *Journal I.E.E.*, 1934, vol. 75, p. 278. † *Physica*, 1934, vol. 1, p. 437.

tance (51) may be imagined to be connected to the negative side of the valve filaments.] The three unit-stages are identical. Any disturbance originating at the grid of the first valve will reappear in the anode circuit with a phase-change of 180°. In passing to the grid of the second valve a further phase-change will be sustained in the condenser-resistance network, and so on. At one definite frequency the interstage phase-change will be 60° and the disturbance will return to the first grid in phase with the initial disturbance. Under suitable conditions sustained sinusoidal oscillations will therefore occur at a frequency determined simply by the value of the coupling purpose. The frequency was, however, successfully stabilized by injecting into one of the grid circuits a small e.m.f. derived from the 4-cycle photocell amplifier even when the natural (uncontrolled) frequency of the oscillator differed from 4 cycles by as much as 10 per cent. Under these extreme conditions, slight wave-form distortion was apparent. In the final circuit the oscillator frequency is stabilized in this manner after having previously been set as near to 4 cycles per sec. as possible, and the voltage stabilizer is retained.

Mention may be made of a key which, when thrown to one side or the other of its normal position, cuts out the

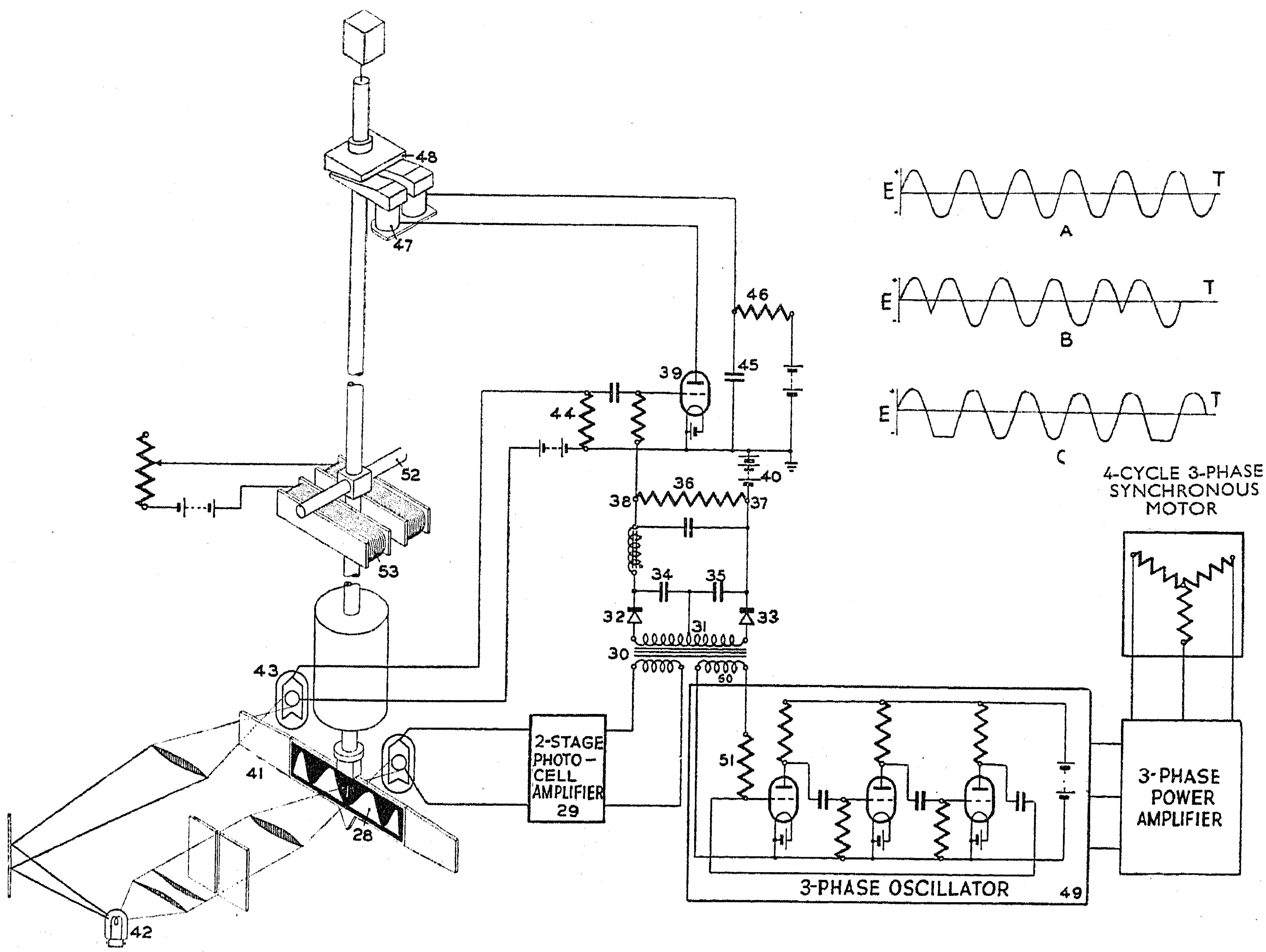

Fig. 7.—Drive for speaking clock.

components. Further, the alternating e.m.f.'s appearing at the three anodes or at the three grids will be in a balanced 3-phase relationship. In practice the unavoidable stray capacitances may produce oscillations in a different mode, usually at a very high frequency. These can be suppressed by shunting one or more of the anode resistances by small condensers which do not affect the oscillations at the lower frequency.

A practical trial of this circuit showed that with suitable values it functioned satisfactorily at approximately 4 cycles per sec., but that the actual frequency varied somewhat with changes in anode voltage. This variation was eliminated by the addition of a neon-tube voltage-stabilizer, but even with this addition the natural frequency was insufficiently constant for the present pendulum control and alters the resistance values in the oscillator circuit so that the speed of the clock mechanism is increased or decreased by approximately 10 per cent. Additional contacts on the key prevent the clock being brought into service except in the normal (i.e. controlled) position. This feature is very useful when starting or restarting a clock which has been stopped either by the occurrence of a fault or for general overhaul.

The output stage consists of three 75-watt triodes coupled to the oscillator by three special transformers which employ mumetal cores to obtain the necessary inductance without undue bulk. A single output transformer is used in order to avoid d.c. magnetization of the core. Variable potentiometers are included between the oscillator valves and the output valves for balancing the

currents in the three secondary windings. The latter are star-connected with the neutral point earthed. Under normal conditions the 4-cycle component in the main H.T. supply to the whole amplifier is negligible and no undesirable feed-back effects have been detected.

The total maximum undistorted output of the amplifier is over 50 watts. The actual consumption of the motor is, however, only about 20 watts. The wave-form of the current in a resistive load at full output is shown in Fig. 8.

Pendulum-maintaining Circuit

It is now evident that the speed of the 3-phase motor and, therefore, the accuracy attained by the whole clock, depend entirely upon the timekeeping of the pendulum. It has been seen that, even using the Hipp escapement, this is good but could be further improved by allowing the pendulum to swing completely freely.

The manner in which this ideal was attained will be apparent from Fig. 7, which is a purely schematic diagram of the whole method of drive. (Batteries are shown for

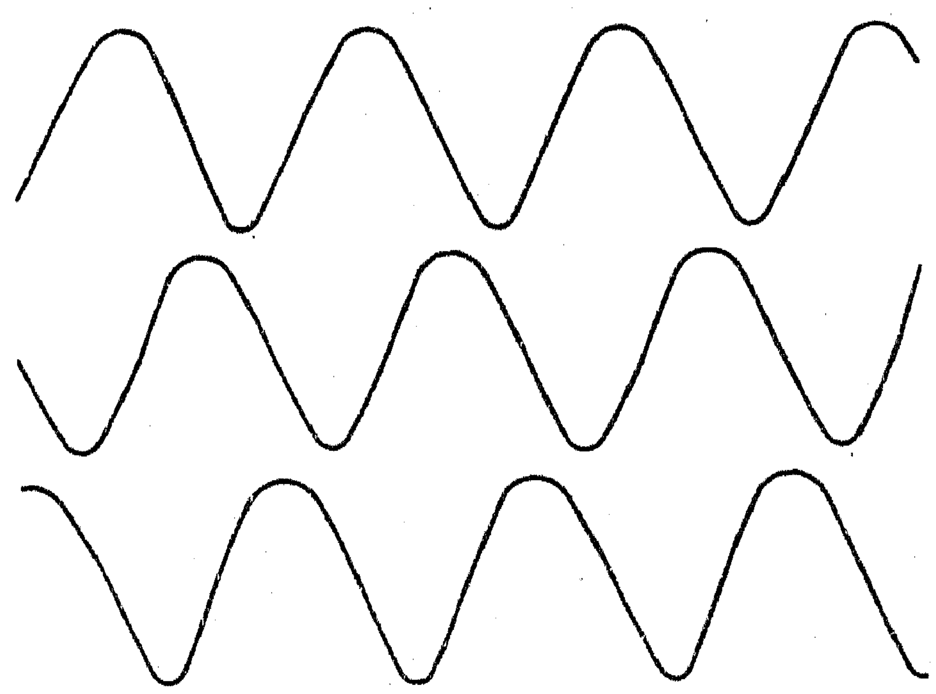

Fig. 8.—Output wave-form of 3-phase amplifier.

the sake of clearness, although the actual equipment is entirely a.c.-operated.) So long as the arc of swing is correct, i.e. equal to the length of baseline of the wave-trace (28), the output wave-form of the photocell amplifier (29) will be sinusoidal.

Oscillograms show that, if the amplitude of swing is slightly too small, the wave-form obtained is similar to curve B (Fig. 7), whereas if the amplitude of swing is too great the shape shown in curve C is produced. The output from the amplifier (29) is applied to a transformer (30) one secondary winding (31) of which has a centre tap. By means of rectifiers (32 and 33) the condensers (34) and (35) receive charges due respectively to the positive and the negative half-cycles of the current. The difference in potential between the two condensers, after smoothing, is applied to the resistance (36). When the amplitude of swing of the pendulum is correct and the wave-form symmetrical (see curve A, Fig. 7) the charges on the condensers are equal; there is then no p.d. between points (37) and (38), and the potential of the point (38) relative to the earth line, i.e. the effective bias applied to the grid of the gasfilled relay (39), is simply that due to the battery (40). As the amplitude of swing falls, the wave-form becomes unsymmetrical [Fig. 7B] and the charges on the condensers become unequal. In consequence a difference of potential appears between points (37) and (38) of such sign that the effective negative bias on the gasfilled relay is reduced. This change of bias is utilized to permit application of a driving impulse to the pendulum as required and at the correct point in the swing.

At the mid-point in each left-to-right swing of the pendulum a shutter (41) allows a narrow beam of light from the source (42) to fall on the photocell (43). An increase then occurs in the photo-electric current flowing through the resistance (44), as a result of which there is a momentary rise in the potential of the grid of the gas-filled relay (39). When the amplitude of swing of the pendulum is correct this rise in potential is insufficient to make the relay conducting. When, however, the amplitude has fallen by a predetermined permissible amount the reduction in effective steady bias produced by the p.d. appearing across the resistance (36) is such that the relay becomes conducting at the instant of application of the impulse from the photocell (43). The condenser (45), which is charged through a high resistance (46), then discharges through the energizing coils of the magnet (47), which, attracting the armature (48), applies a driving impulse to the pendulum and restores normal amplitude of swing.

The small 4-cycle e.m.f. required for stabilizing the frequency of the 3-phase oscillator (49) is derived from a tertiary winding (50) on the output transformer of the photocell amplifier.

It will be apparent that this form of pendulum drive, depending as it does upon slight distortion mainly of the cycles generated at the extremities of the swing, will be more positive in action at low frequencies. The frequency employed—4 cycles per sec.—is therefore a compromise between this factor and the comparatively greater ease of designing the remainder of the apparatus to work at a higher frequency.

A practical trial of this scheme extending over several months demonstrated a considerable increase in accuracy. On the whole, the hourly error rarely exceeded $\pm 0{\cdot}05$ sec. Such larger errors as did arise were ultimately traced to variations in ambient temperature. When the pendulum cabinet was maintained at constant temperature the departures from the mean rate of the pendulum did not exceed 0·05 sec. per hour, and rarely exceeded 0·02 sec. per hour, over long periods.

Construction of Pendulum Unit

The iron casting carrying the pendulum is mounted within an aluminium box built up on a steel framing. The box is supported on substantial rag bolts let into a main foundation wall of the basement of the telephone-exchange building. The effects of vibration are thereby minimized. The pendulum for the second clock is mounted similarly on an adjacent wall at right angles to the first. The method of fixing was designed to give a rigid mounting and allow for accurate levelling.

The optical system is carried directly on the front of the box and adjustments are provided for accurately focusing and centring the whole system. To simplify these adjustments a low-power microscope is fitted for inspecting the image of the slit on the wave-trace.

The pendulum box is contained within a wooden cabinet fixed to the wall. The atmosphere within the cabinet is maintained at a substantially constant tem-

perature by means of heaters and a thermo-regulator; a fan is provided for securing uniform temperature distribution.

Four-cycle Three-phase Synchronous Motor

In view of the low frequency employed it appeared very attractive to dispense with gearing and to design the motor to run at the same speed as the main disc shaft, i.e. 60 r.p.m. An 8-pole rotor was therefore required.

At this low speed the major problem, with a rotor of reasonable diameter, is that of obtaining adequate back-e.m.f. The rotor is therefore worked at a rather high

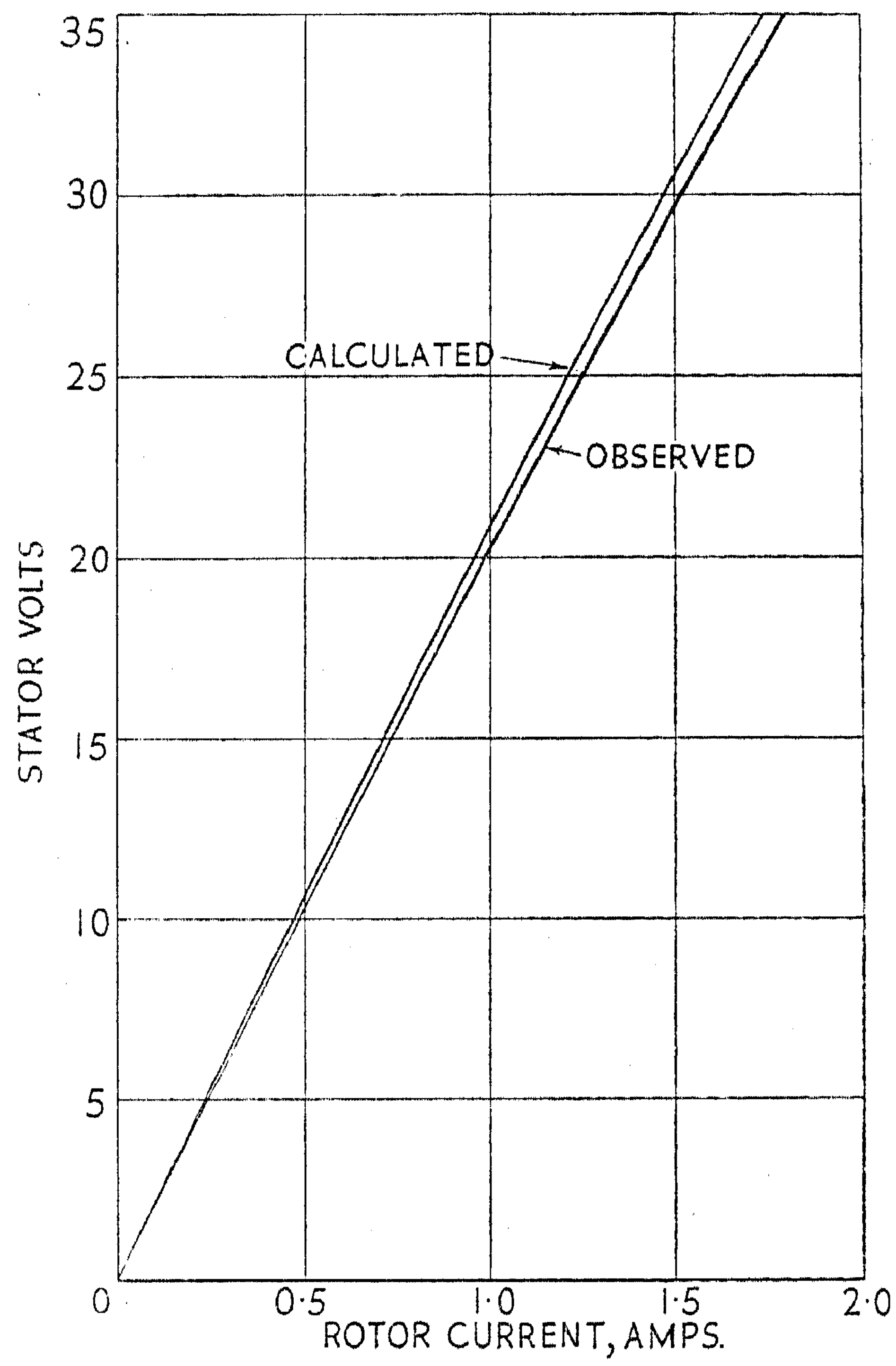

Fig. 9.—Relation between open-circuit stator voltage and rotor current of 4-cycle motor.

flux density. The pole shoes were made detachable for convenience in winding, but apart from these the rotor was milled from a single solid billet. To reduce slot-ripple and improve the wave-form of the back-e.m.f., the pole shoes are skewed.

The stator windings are full-coil, star-connected, and contained in 48 slots. The neutral point is not earthed.

The measured and calculated characteristic curves of open-circuit voltage against rotor excitation of the machine when driven as a generator at 60 r.p.m. with normal excitation are as shown in Fig. 9. The agreement between these two curves and also between similar curves taken under load conditions is good.

TIME CONTROL

The necessity for a periodic check of the timekeeping of the clock has been mentioned. The operations of this check are twofold, namely (*a*) detection and (*b*) correction of the error. The maximum permissible error having been settled as $\pm 0\cdot 1$ sec., it was decided that in order to provide a margin of safety a correction should be applied for any error exceeding $\pm 0\cdot 05$ sec., but that smaller errors should be ignored. For any error exceeding 0·05 sec. the ideal would be to apply an equal correction, but there is little doubt that this would be very difficult to realize. Further, experience both in the laboratory and in the actual running of the complete installation has shown that such refinement is unnecessary. Accordingly, for errors between 0·05 and 0·1 sec. it was decided to apply a correction of 0·1 sec. Similarly for errors between 0·1 and 0·2 sec. a correction of 0·2 sec. is applied. This represents an abnormal condition, and an alarm is given. Errors exceeding 0·2 sec. represent definite faults for which an alarm is given but no automatic correction is applied.

Apart from certain cam-operated contacts concerned mainly with hourly resetting of the correcting circuit, and a contact which is closed from 0·4 sec. before to 0·4 sec. after the beginning of the third pip of each announcement, the most important part of the correcting equipment incorporated in the clock mechanism is a distributor mounted on the motor-bearing pedestal. A rotating brush bridges across from a continuous ring in turn to each of several short segments which are connected to relays in the correcting equipment proper. The circuit of this is shown in Fig. 10. The apparent complexity of this circuit arises from two main causes. In the first place the duration of the Greenwich signal is about 1 sec., as a result of which precautions are necessary to prevent the operation of more than one of the low-resistance relays F, G, M, L, N, K, J, and H. In the second place these relays must be rapid in operation, and as many contacts as possible must therefore be operated by relief relays. The time signal is received on terminals (77) and (78); (one of these is earthed in practice, and an earth-return circuit is used).

The operation of the circuit is as follows. Providing that the error, if any, of the clock does not exceed 0·4 sec., the contact operated by cam 8 will previously have closed, relay FF will have operated, and contact FF1 changed over. Terminal 73 will also be earthed via cam-contact 14 (on "minutes" camshaft). On the arrival of the time signal, relay E operates and contact E1 closes. The particular contact segment over which the rotating brush is passing at this moment will therefore also be connected to earth, and the corresponding one of the relays F to N will operate. If, for the sake of argument, the clock should be between 0·05 and 0·1 sec. slow, this will be relay K. By means of its first contact it will lock in and by means of the second contact operate the low-resistance relay Z. The Z1 contact of the latter removes the earth from the rotating brush and so prevents operation of any other relay connected to the contact segments.

The closing of the third contact of the relay K operates the corresponding high-resistance relay P, which then locks-in via its own first contact. To avoid overheating of the low-resistance relays, each of which absorbs 12·5 watts, they are released 5 sec. after the hour by the opening of cam-contact 10 which, together with cam-contact 8, is on the main contact camshaft.

The second contact of P lights a lamp which gives a visual indication of the error, and the third contact

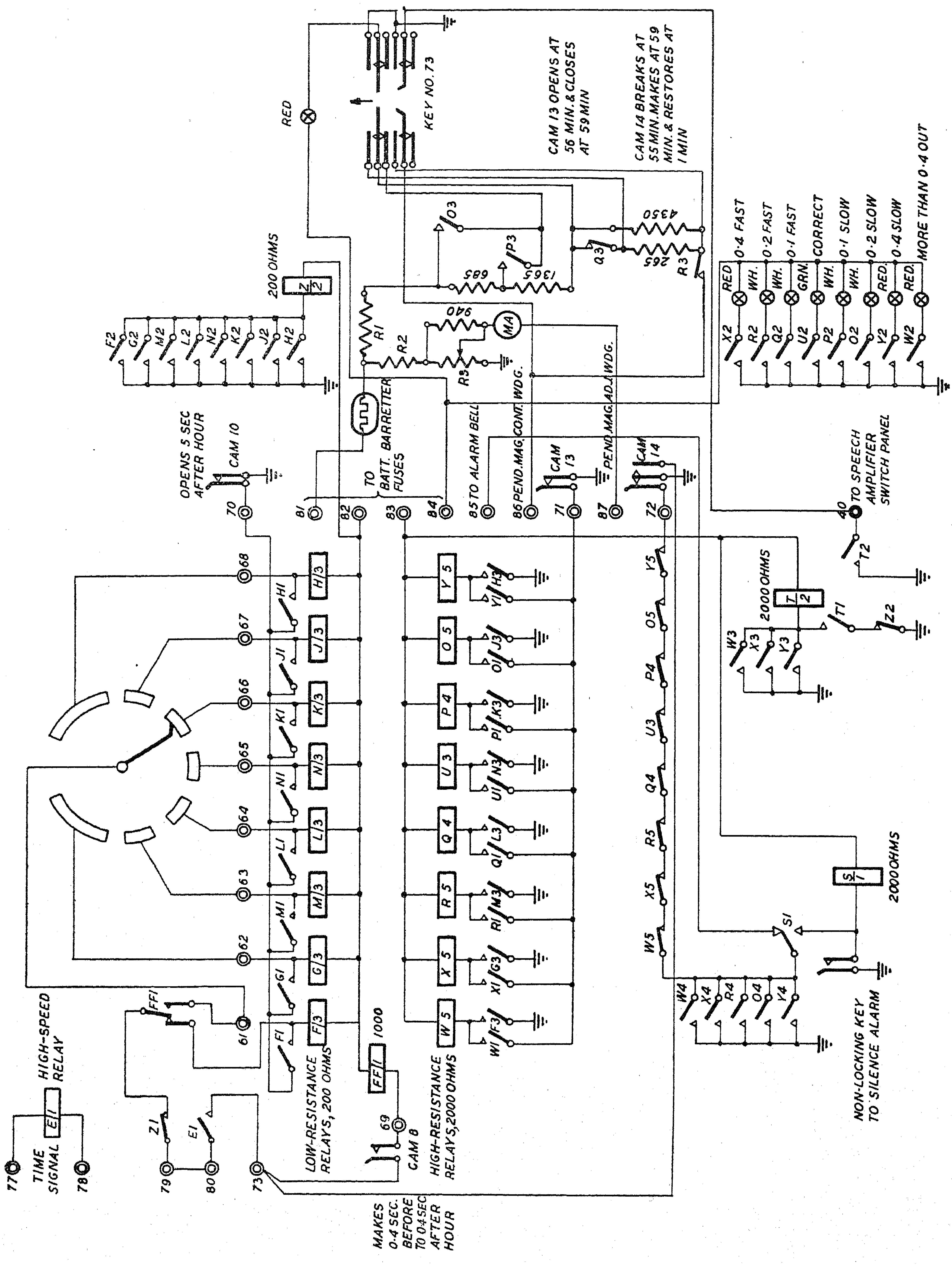

Fig. 10.—Correcting circuit.

applies the necessary correction in a manner shortly to be described. The remaining contact appears in the chain of series-connected contacts associated with cam-contact 14. If no time signal should arrive at any hour, none of these contacts will have operated. On the restoration of contact 14 at 1 minute past the hour an earth connection will thereby be extended to terminal 85 and thence to the alarm bell, which will then ring.

The operation of relay Q if the error is between 0·05 and 0·1 sec. fast is similar, as also is that of relay U if the error does not exceed ± 0·05 sec., with the exception that the latter relay does not apply a correction.

An error between 0·1 and 0·2 sec. will lead to the operation of relay O (if slow) or R (if fast). This is an abnormal, but not necessarily a serious, condition. The fourth contact of these relays makes the alarm connection. This draws the attention of the attendant, but does not automatically remove the clock from service.

The operation of relays Y or X if the error is between 0·2 and 0·4 sec., or of relay W if the error exceeds 0·4 sec., represents a definite fault condition which is indicated by an alarm. No automatic correction is applied for such errors, but the third contact of these relays is used to remove the clock from service. By the closing of one of these contacts relay T operates and this in turn extends an earth to the change-over panel. T locks-in via one of its own contacts and the second contact of relay Z. By this means the service cannot be reconnected to this clock until some subsequent time signal has shown the clock to be within the permissible range of error, i.e. until Z2 has released T and the latter has not again been operated by W, X, or Y. The alarm bell can, however, be silenced by throwing a key which operates relay S.

Five minutes before the hour the cam-contact 14 opens (to avoid giving the "no time signal" alarm), and 1 minute later cam-contact 13 (also on the "minutes" camshaft) opens and restores all the relays (except T) to normal in readiness for the next check.

METHOD OF CORRECTION

In applying the necessary corrections it is essential to avoid sudden changes of speed which might affect the pitch of the voice. The correction is therefore applied gradually. Various possible methods were considered, of which the most attractive and the one ultimately used is control of the rate of swing of the pendulum. This, again, can be accomplished in various ways.

In a simple free pendulum of which the dimensions are fixed the rate of swing is determined by the gravitational force acting on the pendulum. By applying also a vertical magnetic force to a soft iron armature attached to the pendulum, a variation in the effective gravitational force and hence in the rate of swing can be produced. A practical trial showed that by varying the current in the coils of a suitably placed electromagnet adequate control could be obtained without any apparent disturbance of the normal operation of the pendulum. The armature and the magnet are shown diagrammatically as items (52) and (53) respectively in Fig. 7.

In the actual arrangement a certain current normally flows in the coils of the correcting magnet. If the clock should tend to run slow, the closing of contact O3 or P3 (Fig. 10) increases the current in the magnet and slightly accelerates the rate of swing. Conversely, if the clock tends to run fast the opening of contact Q3 or R3 reduces the current and retards the rate. In each case the alteration in rate is effective during the succeeding hour and effects the necessary correction.

This method has the additional advantage that by altering the setting of the potentiometer R3 the current in a second winding on the magnet can be varied in order to make fine adjustments to the mean rate. The effect of such adjustments may be observed by throwing key No. 73. This renders the automatic correction ineffective and earths terminal (40), so that the clock cannot be brought into service until normal conditions are restored.

The effectiveness of the time control as a whole may be judged from Fig. 11, which shows the errors recorded on both clocks during the second week of public operation of the service.

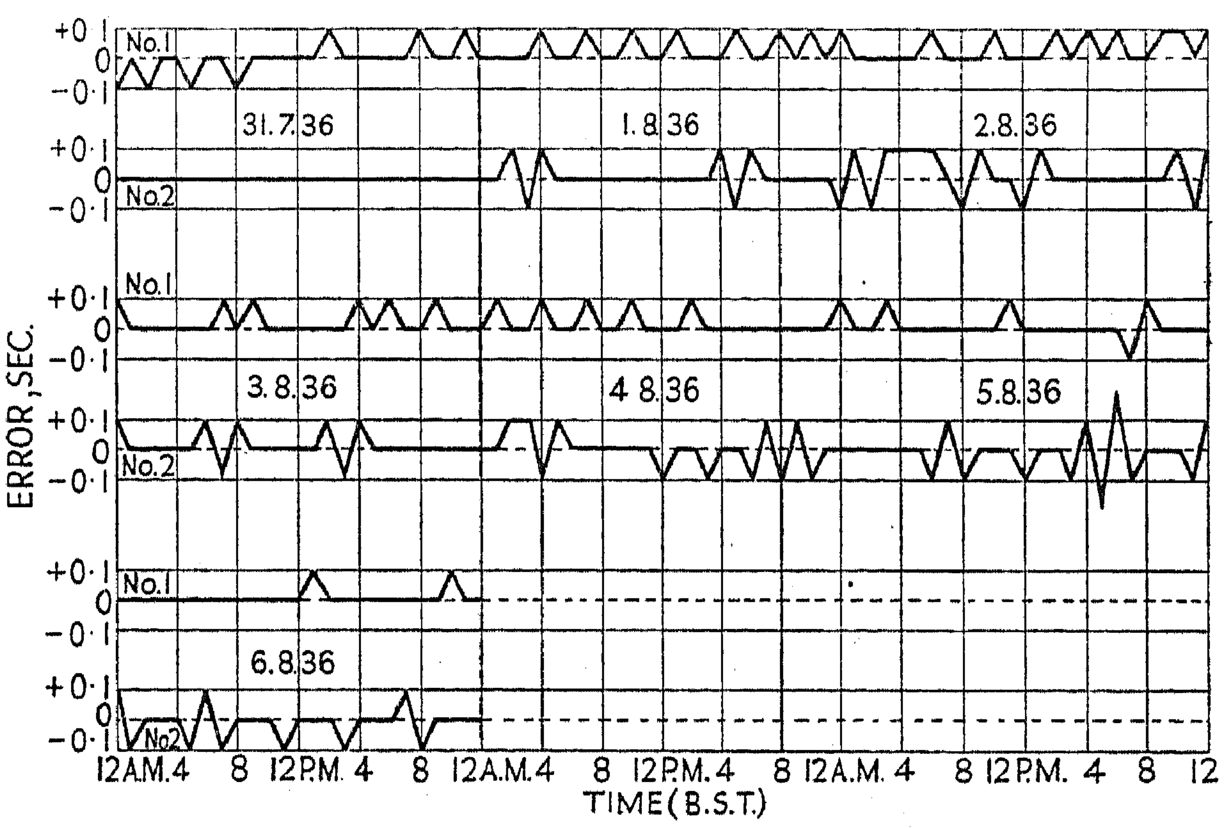

Fig. 11.—Hourly errors of speaking clock during week 31st July–6th August, 1936.

STANDBY ARRANGEMENTS

One of the main aims of the designers of the clock equipment has been to preserve the continuity of the service. For this reason standby equipment, which can be brought into service in an emergency, is provided wherever possible. To avoid unduly complicating the individual mechanism the scheme adopted includes the installation of two duplicate complete clocks.

It is not possible to start up an idle clock, adjust it to give correct time, and bring it into service, by any simple and rapid means of automatic change-over. Hence to avoid lengthy interruptions of the service both clock mechanisms are always running and in correct adjustment, except when one is temporarily shut down for maintenance. Only one speech amplifier, however, is in operation for supplying the service.

The faults which may occur fall into one or other of two broad classes—speech faults and timing faults. The manner in which these are dealt with may be seen from the circuit shown in Fig. 12.

It may be assumed that No. 1 is the working clock, and the functions of relays V and VV and their contacts may be ignored for the moment. Under normal conditions the output to the subscribers' relay sets (terminals 17 and 18) is taken from terminals 10 and 11 of the

speech amplifier No. 1 via the change-over switch and A1 contact. On the appearance of a fault in the speech amplifier, terminal 16 is earthed, causing operation of the relays A and AA. Contact AA2 closes, operating the alarm bell, and A2 connects the mains to the standby speech amplifier and to the corresponding indicator lamp. Until the standby amplifier warms up, no output is hot and giving output the earth is removed from its terminal 16, relay B restores, and the standby takes over the service via the change-over contact A1, which remains operated. Upon manual operation of the change-over switch, No. 2 becomes the working clock, relays A and AA restore, and attention may be directed to clearing the fault on No. 1. For adjustment purposes a tumbler

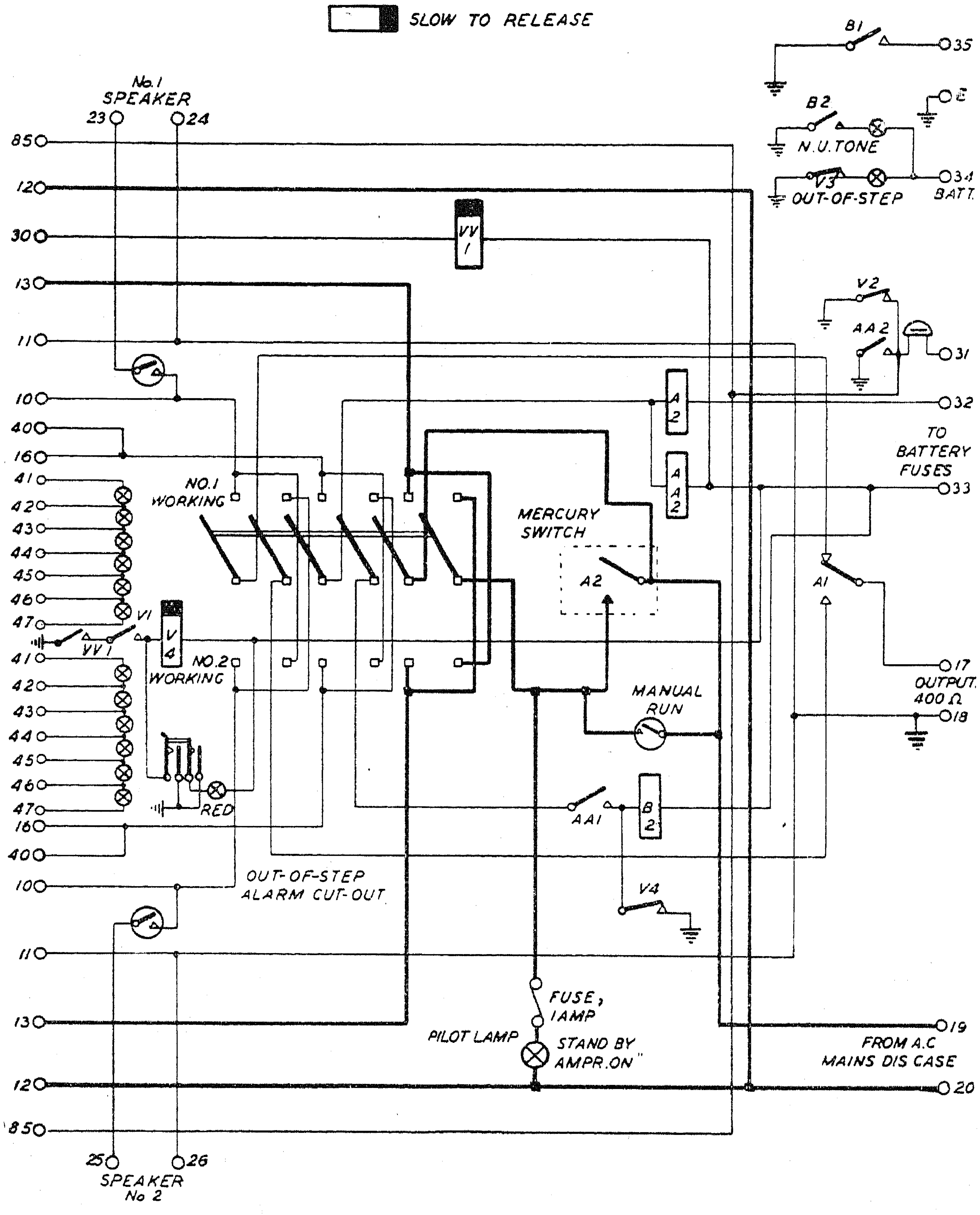

Fig. 12.—Speech-amplifier switch panel.
Thick lines indicate mains leads.

available, and terminal 16 of this amplifier is also earthed. Since AA1 has closed, the relay B also operates. Contact B1 earths terminal 35, which is connected to the relay sets, and causes " number unobtainable " tone to be sent out to subscribers. Contact B2 causes the corresponding indicator lamp to light. In the unlikely event of the standby amplifier also being faulty or out of service, this condition persists until the prime fault has been cleared. In general, however, as soon as the standby amplifier is switch shunting the mercury contact A2 can be closed to switch on the standby speech amplifier if required. Switches are provided to connect loud-speakers across the output of either or both clocks for monitoring purposes.

In the event of the working clock developing an excessive time-error a similar series of operations occurs, except that terminal 40 receives the earth connection. Under " no time signal " conditions the alarm is given by the earthing of terminal 85 but there is no change-

over since, if the indication is genuine and not due to a cause such as a dirty contact, the actual fault will probably be external to and will affect both clocks simultaneously.

It will be apparent that the operations just described can deal only with the small errors registered at the hourly checks. Under abnormal conditions, however, a large error might arise and go undetected until the next check. Thus failure of the pendulum exciter lamp or of a valve in the photocell amplifier would permit the oscillator to run uncontrolled, or faulty operation of a clutch mechanism might immediately produce a large error. To deal with this kind of fault advantage is taken of the fact that it is extremely unlikely that such errors would arise in both clocks simultaneously. Thus the fault condition would be indicated by the clocks running out of step. Arrangements are made to maintain a continuous circuit from earth to terminal 30, whereby the slow-to-release relay VV is held operated, as long as the two clocks are in step. In the out-of-step condition this relay drops out, followed, if the circuit interruption is long enough, by the similar relay V which is not self-resetting. The second contact of V rings the alarm bell, the third lights an alarm lamp, and the fourth causes relay B to operate, whereby the service is discontinued and "number unobtainable" tone is sent out. There is no change-over, since there is no automatic means of telling which clock is at fault. An out-of-step alarm cut-out key is provided for resetting after clearing of the fault, and also to prevent an alarm condition arising if the standby clock is deliberately stopped for any reason. This facility is provided with the aid of distributors associated with each camshaft, two of which are shown (54) in Fig. 4. The number of contacts on each is the same as the number of teeth on the corresponding ratchet wheel. Corresponding contacts on the two sets of distributors are wired together, and the rotating brushes are connected so that a continuous circuit involving all these distributors exists as long as the two clocks are in step. The use of two slow-release relays in tandem in the alarm circuit is necessary to avoid false operation due to the unavoidable momentary interruptions in the circuit when the camshafts move from one step to the next.

GENERAL LAYOUT OF INSTALLATION

The whole of the equipment so far described is installed in a special room. The two mechanisms are carried on substantial tables on one side of the room and protected from dirt by glass-panelled covers. The amplifiers and control panels are mounted on four 19 in. × 7 ft. standard racks on the opposite side of the room.

It has been found by experience that the gasfilled relays in the pendulum drive-circuit function erratically at extremes of ambient temperature. For this reason the artificial ventilation and heating arrangements are arranged to permit thermostatic control of the room temperature at a few degrees below the temperature within the pendulum cabinets.

POWER SUPPLIES

The main requirements of the power supplies are simplicity and reliability. All the d.c. equipment, i.e. the rotors of the synchronous motors, the relays, the pendulum control, the shutter and clutch magnets, and the alarm lamps and bells, are worked from the 50-volt exchange battery. No standby is provided since a failure of this supply is most unlikely and, in any case, would prevent any calls being made to the clock. The total consumption is about 250 watts.

The amplifiers, exciter lamps, and pendulum heaters, are worked from the a.c. public supply mains and together consume about 1 800 watts under normal conditions. In this case a standby supply is necessary and is provided by two motor-generator sets of 2·5 kVA capacity. One of these is always running light on the exchange battery. In the event of the mains voltage—normally 200 volts—falling below 170 volts the generator takes over the load. The load automatically returns to the mains when the voltage of the latter exceeds 190 volts. The control gear for this equipment is normal except that the main contactors are perhaps more rapid in action than is usual. Repeated tests under artificial fault conditions have shown that change-over and restoration of the power supply occur smoothly and without introducing errors of timekeeping.

DISTRIBUTION OF THE SERVICE

Few features of the distribution of the service call for special comment. The relay sets at present permanently installed can cater for 100 simultaneous calls. Individual calls are routed to these sets in the normal manner.

The speech output is taken across the 1-ohm resistance connected across the secondary winding of the second output transformer. Although incorporated primarily in order to maintain a constant volume level, this resistance also introduces sufficient attenuation between subscribers who happen to be simultaneously connected to frustrate attempts at conversation.

To avoid difficulties in switching, whether carried out by means of direct current or of voice-frequency currents, a 2-μF condenser and a 200-ohm resistance are included in both leads between each relay set and the output transformer.

To avoid congestion it is necessary to limit the time during which a subscriber can remain connected. An automatic forced release is therefore applied which, according to the instant when the connection is established, disconnects the call after 90–180 sec. In the worst case 8 complete announcements will thus be heard.

The occurrence of a major alarm condition, i.e. one necessitating temporary interruption of the service, causes the operation of relays which disconnect all subscribers from the clock output and send out "number unobtainable" tone. During such periods non-metering conditions apply.

It was expected that immediately after the official opening of the service by the Astronomer Royal on 24th July, 1936, and particularly after a transmission of the clock in the Second News Bulletin broadcast by the B.B.C., very heavy curiosity traffic would occur. Precautions were taken to deal with this. In the first place, the forced release was set to operate after two-thirds of the normal period had elapsed. Secondly, calls made through manual exchanges were connected direct to the

output transformer via special reserved junctions to avoid using the ordinary relay sets; and finally, calls in excess of these provisions were routed to a special number on Mayfair exchange and dealt with by means of temporarily-installed amplifiers and relay sets. By this means the maximum number of calls simultaneously connected rose to 280. The introduction of the service in the late afternoon avoided much of the inconvenience to normal traffic that would otherwise have arisen.

During the first week of public operation of the service nearly 400 000 calls were made, and during each subsequent week the number has remained practically constant at about 200 000, i.e. approximately 8 times the volume of traffic received before the introduction of the service.

CONCLUSION

In conclusion, the authors wish to express their thanks to Sir George Lee, O.B.E., M.C., Engineer-in-Chief of the Post Office, and Mr. B. S. Cohen, O.B.E., of the Research Branch, for permission to publish this paper. They also desire to express their appreciation of the help received from their colleagues in connection with many points of the design, and from Mr. E. J. Wender, late of British Acoustic Films, Ltd., in the preparation of the sound discs.

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 4TH DECEMBER, 1936

Mr. B. S. Cohen: I think the best contribution I can make to the discussion is to give some information with regard to the service that has been provided since the speaking clock came into operation. Mr. W. C. Griffith, of the London telecommunications region, who has had much to do with the introduction of an automatic time service in this country, has kindly furnished me with some data.

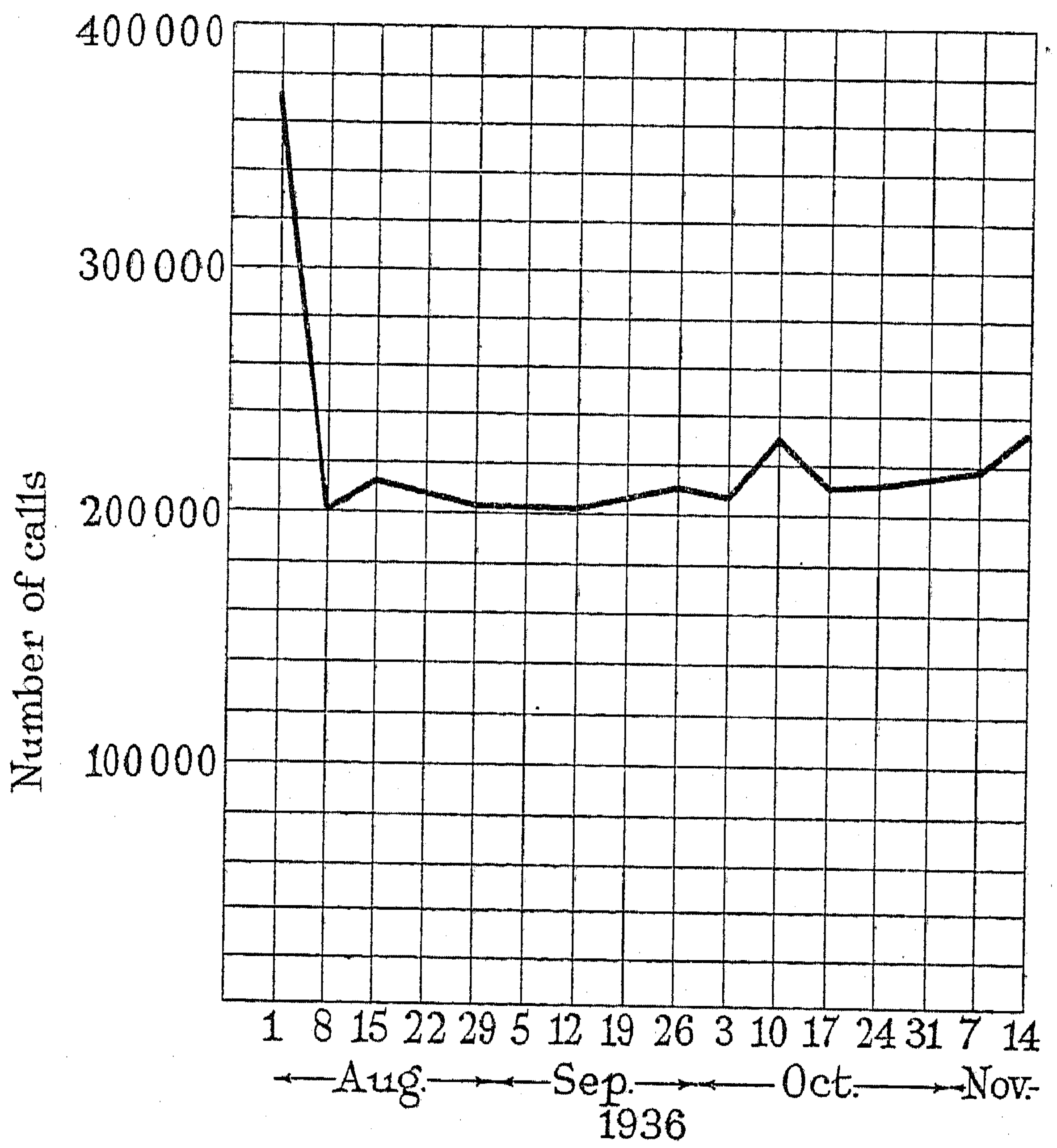

Fig. A.—A weekly record of calls to the speaking clock, starting with week ended 1st August, 1936.

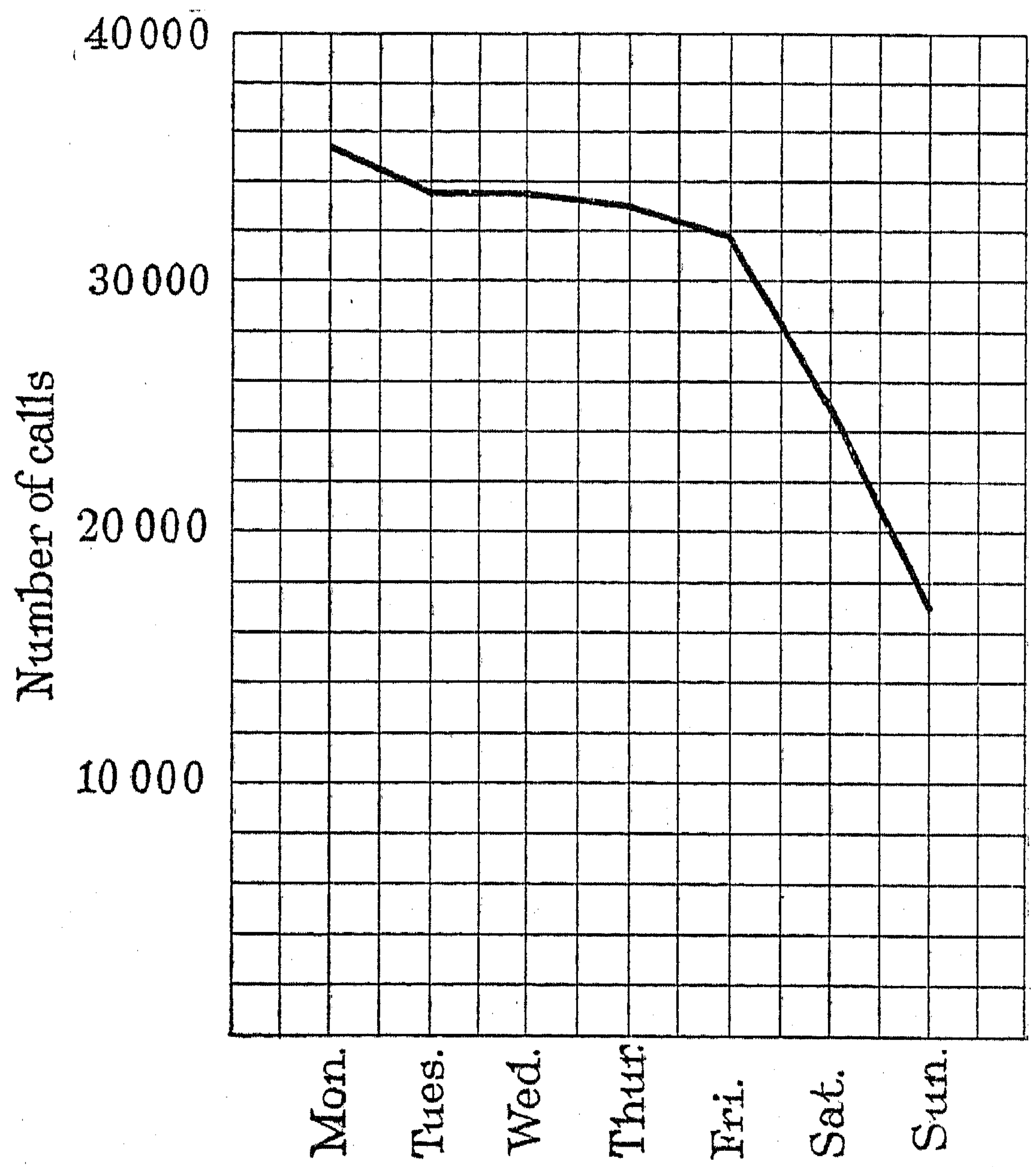

Fig. B.—Daily record of calls to the speaking clock.

Fig. A gives the weekly traffic from the inception of the service up to the week ending 14th November, 1936. It will be noticed that the curiosity traffic referred to by the authors disappears at the end of the first week, and from then onwards the service is maintained at about 200 000 calls per week, with a slight but steady increase. This increase is being well maintained and somewhat accelerated. There are two interesting peaks in the curve. The first occurs in the week 4th–10th October, and is mainly due to the change-over from summer to winter time. As a matter of fact, a large number of people appear to have sat up most of the night to find out what happened when the speaking clock transferred from 3 o'clock according to summer time to 2 o'clock according to winter time. I may say that nothing happened except that the 10-second announcement prior to the 2 o'clock winter time was that: "At the third stroke it will be 2.59 and 50 seconds," and the next announcement was: "At the third stroke it will be 2 o'clock precisely." The other increase, observed in the week 7th–14th November, was accounted for by the number of people who wished to call up on Armistice Day to find the right time just before the two minutes' silence.

Fig. B shows the distribution of the calls during a week, averaged over several weeks. Monday is the day on which most people call up; the number of calls seems to keep fairly level until Friday, when a big percentage of the population of London apparently loses interest in the time.

Fig. C shows the distribution of the speaking-clock service as compared with the distribution of the ordinary telephone service. (The time service is on a scale 100 times greater than that applying to the telephone service.) It will be observed that the speaking-clock service, which is represented by the dotted line, conveniently produces its peaks in the valleys of the ordinary telephone service, thus providing what both the telephone engineer and the supply engineer will agree is an ideal distribution. The telephone service and the electric supply service have the same difficulty, namely that their plant is built up on their peak requirements. It is the busy-hour requirement that settles the capacity of the telephone plant, and therefore the calls that occur during the busy hour may produce very little or no profit, or even a slight loss, whereas the calls during the other times produce quite a substantial profit. Another factor which helps to make the time service particularly profitable is the short holding time. The holding period for the time announcement is only that represented by several of the 10-second announcements, whereas the average time of a telephone call may be 3 minutes or more.

The success of the speaking clock leads one to consider the possibilities of finding other forms of by-product services which could be dealt with in a similar way. Stockholm has a weather service which is very well patronized, especially at week-ends. The weather announcement is obtained by dialling certain appropriate letters. This type of service might prove popular in this country, with its very variable climate.

Mr. F. Hope-Jones: Mr. Cohen described the speaking-clock service as a profitable one, and I should be interested to know how it compares with the French service in this respect. The latter is most remunerative, and such a service is more urgently needed in France where the other time services are not as good as in this country. France has no "six pips" like those with which our broadcasting service provides us, and she has no national "grid" timed to an average Greenwich frequency.

The feature which outshines everything else in the Post Office installation is the brilliant idea of scanning a sine wave with a moving pendulum in order to produce the slow alternating current for not merely the control but also the running of the motor. There have been many different ways of imposing accurate time upon the speed of motors, but so far as I know this method is absolutely original. It overcomes the great difficulty of how to obtain a low-speed motor of real accuracy for use in time measurement. A good deal has been written about the methods of tone production for imitating organ pipes, and the method which outshines all the others is a system of wave-scanning remarkably like that employed in the speaking clock.

Mr. A. O. Gibbon: I am interested to find that a part of the Post Office electrical master clock, known officially as "clock No. 36," which is in use in all our large telephone exchanges, has found a humble but important place in the mechanism of the speaking clock. This type of master clock not only provides the time service in our telephone exchanges but also operates time relays in connection with the duration of calls. In one of the London city exchange buildings, for example, there are associated with one such clock, 74 secondary clocks and 2 000 time-impulse relays; indicating the useful part taken in our telephone system by clock No. 36. The clock is specified to maintain accuracy of timekeeping to within 6 sec. per week.

The automatic regulation applied each hour from Greenwich is of value in synchronizing the speaking clock, and illustrates the important part which the Royal Observatory plays in the time services of this country. The "high spot" in time distribution is effected through Greenwich and Post Office co-operation in the Rugby radio signal, which is of extreme accuracy and transmits correct time throughout the whole world for astronomical and commercial purposes. It is true to say, however, that the Astronomer Royal has not always found a willing and appreciative public in connection with time correction from Greenwich Observatory. I learn from a report made by Sir George Airy in 1849, who originated the idea of electrical control of public clocks, that: "The general utility of the

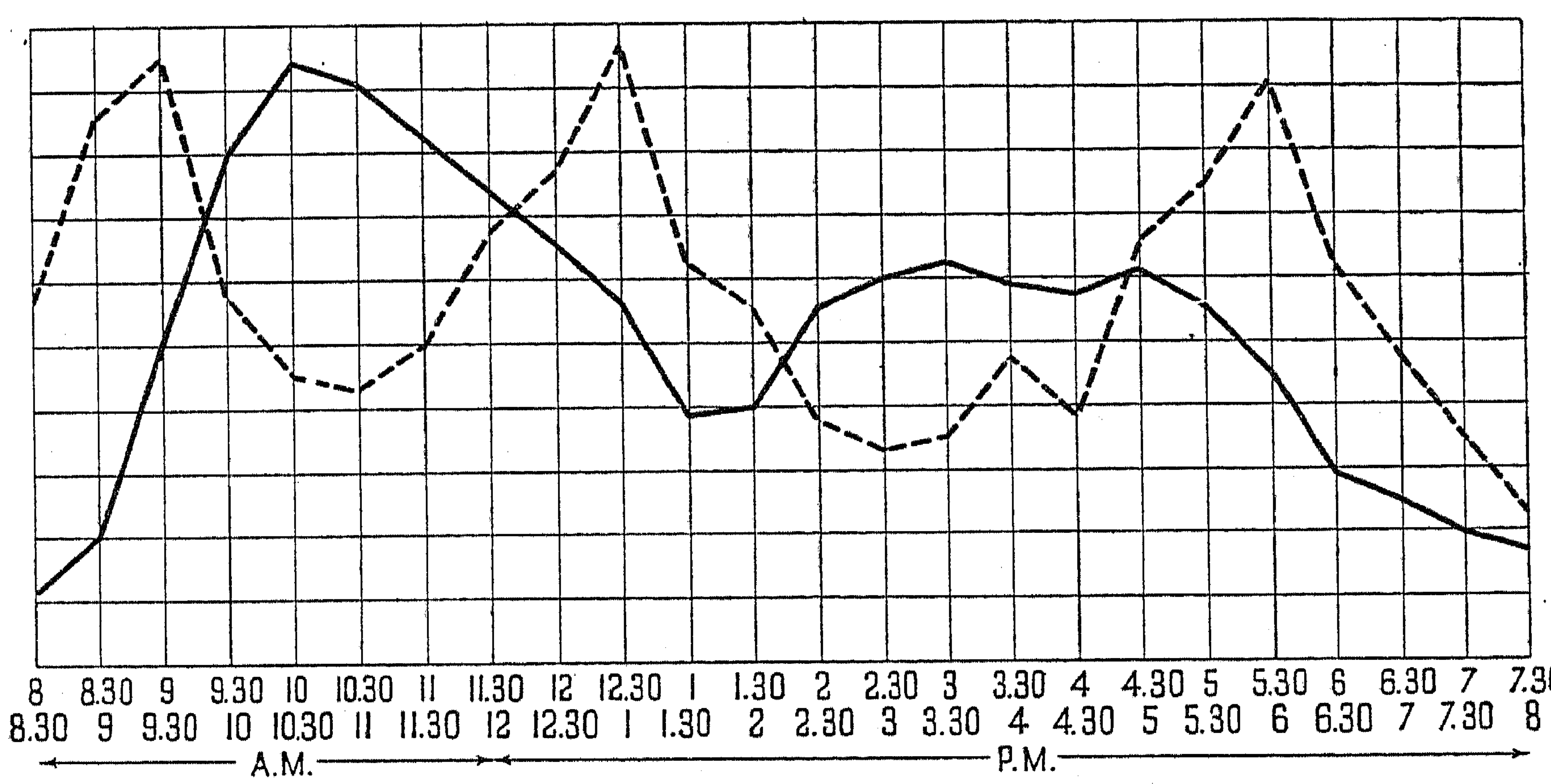

Fig. C.—Average of records for 6th, 7th, and 8th October, 1936.
——— Total calls originating within the 10-mile circle, including calls from manual exchanges and automatic assistance calls.
– – – – Total calls to the speaking clock.

Observatory will be increased by the dissemination through the kingdom of accurate time signals by an original clock at Greenwich, and I have entered into correspondence with the authorities of the South-Eastern Railway." In 1856 Sir George Airy reports: "One of the galvanic clocks in the Post Office Department at Lombard Street is already placed in connection with the Royal Observatory and is regulated at noon every day, sending also a signal before noon to inform me how far it is wrong, and in the afternoon to assure me of the efficiency of the correction. Other clocks at the General Post Office are nearly prepared on the same lines. In a difficulty attendant on a new enterprise of this kind there is caused to all the parties an amount of trouble which cannot be adequately expressed by money. I can only express my thanks for the aid of Mr. Latimer Clark, who has given me his help in a very annoying series of experiments."

I wish to put forward two suggestions concerning the further development of the popular speaking-clock service. In view of the considerable revenue received from this source, it might be found possible to charge all subscribers in the London Telephone Area the same flat rate for the use of the time service. There would also appear to be a field for an early extension of the time service to the large provincial centres.

In a paper* read before the Institution of Post Office Electrical Engineers 6 years ago, it was conjectured that "The master clock at the telephone exchange may provide a time service direct to subscribers by means of their telephone circuits." Reference was also made in the paper to the automatic intimation to the public of elapsed time on trunk calls and the hope was expressed that the automatic voice would be a musical one, preferably a lady's voice; "in any event the automatic voice should not overlook aesthetic requirements."

The speaking clock gives us the time by means of a lady's voice, and so far as an automatic record *can* produce an aesthetic result this has also been secured!

Mr. H. J. Gregory: I think it is correct to say that, prior to the introduction of the TIM service, the Paris speaking clock was the only one in service having the same accuracy, but there is an important difference between the two installations. The Paris clock is installed in the Observatory and its output is fed over a line to the telephone exchange for distribution. The Post Office clock is installed in the telephone exchange and its maintenance is part of the normal duty of the staff there; consequently the design of the speaking-clock equipment had to conform as much as possible to telephone engineering practice. Only one pair of clocks have been made to this design, and it will be agreed that it is a fine piece of work, especially when it is considered that owing to the urgency of getting the service started in view of the publicity campaign, the experimental work had to proceed simultaneously with the actual construction.

Dr. W. G. Radley: One or two features of the Paris clock may be of interest, particularly since it has been in operation for about 4 years. When work was started on the design of the Post Office installation the Paris clock set a standard of service and of reproduction which had to be equalled, if not excelled.

The conception of a time service in Paris originated at the Observatory as a result of the numerous telephone calls which were received for the correct time. The Observatory was responsible for the construction and, as Mr. Gregory has told us, is responsible for the maintenance of the clock. A single circuit connects the clock with the telephone exchange about $\frac{1}{3}$ mile away, at which arrangements are made for connection simultaneously to 60 subscribers. To answer a question put by Mr. Hope-Jones, the traffic in Paris averages about 80 000 calls per week; the volume of traffic in London is thus about $2\frac{1}{2}$ times that of the Paris traffic. The French telephone administration pays to the Observatory a small sum—I believe 5 centimes—per call.

The method of mounting the speech records in the Paris clock possesses attractions from a constructional point of view. The records are on photographic paper, and the speech is reproduced by light which is reflected and scattered into the photocell. The Post Office considered the possibilities of reproduction by a similar method, but, although in the early descriptions of the French clock it was claimed that the reproduction did not suffer in quality on account of the method employed, considered opinion led to the use of reproduction through a transparent film. The French voice is that of a well-known announcer of Radio Paris. In the case of the French clock, the switching necessary in the building-up of the phrase, i.e. to allow the hours, minutes, and seconds to be heard in their right sequence, is done electrically and not, as in the case of the British clock, optically.

Two clocks are kept running simultaneously at the Paris Observatory, as with our system. There is no automatic transfer of the service from one clock to the other, but the output is continually monitored on a loud-speaker, and, in case of need, the service can be transferred from one clock to the other by throwing over a single switch.

Photographs of the two clocks emphasize the difference in size of the two driving motors. The explanation is that the motor of the French clock runs at a high speed and drives through reduction gearing. When designs of the English clock were first prepared elimination, as far as possible, of all gearing was aimed at, although this meant a very low-speed motor. The large size of the motor is due entirely to its speed, and not to the abnormally low frequency. There is a fundamental difference between the drive of the Post Office speaking clock and that of all other speaking clocks which might well be emphasized. The motor rotating the Paris clock, for instance, is controlled through a "Gerrish" drive. Once in each swing a pendulum closes a contact which actuates a relay and connects power to the motor until the circuit is broken through another contact on a disc forming part of the driven mechanism. Thus power is connected during a part only of each revolution of the mechanism. If the mechanism is gaining on the pendulum the period during which the power is connected is reduced, and vice versa. There being this switching on and off of the power, some cyclic variation in the speed of the motor, however slight, must occur, with a consequent effect on the speech reproduction. This

* A. O. Gibbon: "The Electrical Control of Time Services in the British Post Office," Institution of Post Office Electrical Engineers, Professional Paper No. 135.

is the general principle of all controlling systems except that of the British clock, where the drive is continuously applied. The difference is that between periodic checking of the speed and continuous control.

Mr. W. C. Griffith: It is of interest to realize that the speaking clock has created an addition of 1 per cent to the total traffic in the London telephone area. The speaking clock is now by far the most frequently called "subscriber" in London. It is unfortunate that the newspaper publicity which has been given to the clock seems to have left the public with the impression that the clock is only available by dialling, i.e. to subscribers on automatic exchanges, and has not sufficiently emphasized the fact that the service is also available to subscribers on manual exchanges. Forty per cent of our subscribers in the 10-mile radius are still connected to manual exchanges, and we have found that they produce only 11 per cent of the traffic to the clock. This is to be corrected by some further publicity particularly directed to subscribers on manual exchanges.

Mr. Cohen referred to the Armistice Day peak on the total traffic. It is an extraordinary fact that whereas normally between 10 a.m. and 11 a.m. we get about 1 750 calls to the clock, on the morning of the 11th November we successfully handled 14 000, but we have no knowledge of the number of ineffective attempts made to get connection to the clock during that period. Up to 10.40 a.m. we were handling the traffic successfully, but between 10.40 and 11 we were, to some extent, overwhelmed. We had largely increased the traffic capacity of the clock to provide for the increase in traffic, but there is always a limit to what can be done in that direction, and we were not able to hold that 20-minute peak. We are expecting another very large demand just before midnight on New Year's Eve, but I hardly think it will reach the dimensions of that particular 20 minutes on Armistice Day.

Another factor which works in our favour, in addition to the distribution factor and the duration factor, is the negligible percentage of ineffective calls for TIM. Ineffective calls represent a definite drag on the cost of running the telephone service. Normally we get, in connection with this "time" service, no "number engaged" and no "no reply" calls, which are our main sources of loss in connection with ordinary calls, and thus we work very much nearer to the "100 per cent effective calls" standard in calls to the speaking clock than in the ordinary telephone traffic.

Mr. Cohen also referred to the change from summer time to Greenwich time, and explained that "2.59 and 50 seconds" was followed by "2 o'clock precisely." I may perhaps mention how this sequence was arranged. It will be remembered that in the clock the hour is changed by a little cam worked by the relay which moves the optical mechanism from one track to another. Dr. Speight conceived the very simple and clever idea of arranging for the time-change by the process of holding his finger on that relay at 3 a.m., with the result that the optical mechanism controlling the hour announcement was not shifted from the "two" track to the "three" track, as it would otherwise have been, and "2.59 and 50 seconds" was therefore followed by "2 o'clock precisely." I understand that Dr. Speight is looking forward to sitting up again on the appropriate day next April to give the relay a second flick by hand, and so to make it move from "1·59 and 50 seconds" to "3 o'clock precisely" when summer time comes in.

Another point of interest concerns calls from call offices. This type of traffic is normally worked on a system whereby the person who is being called cannot hear the caller until the caller has pressed button "A." It is obvious, therefore, since one would not want to speak to the clock, that unless special arrangements were made it would be possible to obtain the time without payment. Matters are so arranged, therefore, that if one dials "TIM" from a call office one gets the "number unobtainable" tone. Calls from call offices for time must be obtained via an operator, who collects the fee before connection is given.

A great deal of care was taken to find an operator having a very beautiful voice, which Miss Cain certainly has. Operators from all over the country were invited to apply, and there were very many competitors. These were divided into convenient groups, and candidates were chosen from these groups by small committees. There were further eliminating trials, and eventually 15 operators came to London for the final trials. The final adjudicating committee was under the chairmanship of Mr. Masefield (the Poet Laureate) and consisted of Dame Sybil Thorndike, Mr. Hibberd (the chief announcer at the B.B.C.), Lord Iliffe, and a representative subscriber. This committee of 5 heard the candidates solely through the telephone; they did not see any candidate in person until they had made their final choice.

Mr. L. L. Tolley: I should like to draw attention to Fig. 11, which shows the record of hourly errors of the clock installation. More recently the number of errors has been very much less than that shown in this diagram, which was taken soon after the clock had been brought into service, and it may be that the authors can give us some idea of the most recent position. I should like to ask them also whether there is any correlation between the incidence of such errors as do occur and the time of the day; for example, whether the traffic —which, of course, is heavy in Holborn during the day— causes or prevents errors of this type.

Mr. Gibbon suggested that the extension of the service to the whole country would be of benefit, and he seemed to indicate that a large number of clocks situated all over the country would be necessary. The existing installation is capable of doing a great deal in that direction. The authors mention that 100 relay sets are worked from it; but it is capable of dealing with four times that number of direct subscribers, and where amplifiers are fitted at the distant end of the line it can, of course, deal with thousands. The only difficulty is that, since the lines have a finite transmission time, the three pips received in Glasgow, for example, would not occur at exactly the same time as in London, there being a difference of some thousandths of a second; and the difference between Manchester and London would be half that number of thousandths of a second.

In addition to a territorial extension of the time service there is possible an extension of the type of service. The authors have described the function of the commutators on the camshafts of the clock which

determine the position of those camshafts, so that the two clocks give the alarm condition if they differ from one another by any appreciable amount. The same set of contacts on those commutators could, by a simple alteration of the circuit, be arranged to pick out one particular announcement and to provide that only to one particular circuit or to any selected batch of subscribers. This might form an extension of the service over and above the public time service.

Mr. F. Jervis Smith: The authors say that the device having the shortest life and needing the most frequent replacement is the exciting lamp for the photocell, and they attempt to secure better performance by under-running the lamp. Have they found it necessary in practice to apply under-running in some form or other to the valves and the gas-filled relays; and, if so, to what extent?

Mr. E. H. Miller: With regard to the question of new outlets for the Post Office telephone service, I should like to mention that when I was in Paris about two years ago I remarked to my friend in his office: " It is just 6 o'clock. I am sorry you have not the wireless here, because I should like to listen to the news." Replying that I could do that without difficulty, he rang up on the telephone, and the news came through. It is possible in Paris to obtain the news at any time by making a telephone call; presumably the news is recorded, and retransmitted on demand. It seems to me that this would be a most useful thing for our own Post Office to do. If one could for a twopenny call obtain the latest news by telephone at any hour of the day or night, I think it would be a very useful as well as a very remunerative service.

Mr. Albert Page: I understand that in the installation at Holborn there are two speaking clocks running simultaneously, and that, in the event of a failure of one, the switch-over to the other is automatic. Are both installations continuously in step and working, because, if this is so, there is double wear and tear all the time; or is there a device by which the double wear and tear is avoided?

Mr. E. S. Ritter: In Fig. 7 of the paper, item 49, a 3-phase oscillator is shown, and a condenser is indicated at each end of it. Is this correct, or should only one condenser be shown?

Mr. S. J. Smith: It is interesting to speculate on the future of timekeeping and its distribution, and to view the possibilities of a continuously-radiated time service such that, instead of being troubled with broken mainsprings, we should simply switch-in a little tuner which would be carried instead of a mechanical watch.

I am looking forward to the abolition of our present 24-hour system, in place of which there would be an international distribution of time, based on the sun's travel over the lines of longitude, each of which would be given a fixed time value, universal time being accepted by all nationalities as that line of longitude, or its subdivision, over which the sun was passing at any particular moment. I think it should be the aim of scientists to bring about such a system of timekeeping, as one of the means of achieving international understanding and of doing away with the present difference in time, for example, in New York as compared with Greenwich.

Prof. D. Robertson (*communicated*): The implied claim on page 504 that the correct phase for impulsing the pendulum is at the middle of the swing is in accordance with an old horological tradition which has no real foundation, although it may be approximately true for some methods of maintaining the swing of the pendulum. A few years ago, an attempt made to trace the origin of this tradition ended in a reference to example 7 of Airy's elegant paper of 1826:* but that example gives no support to the idea, apart from the fact that it is the only one in the paper in which an error has been made. It is probable that the tradition has arisen from the confusion, still common, between the constant *deviation* of the rate of the pendulum by a constant driving force (which is allowed for when the pendulum is adjusted) and the rate *errors* caused by erratic changes in the amount of that force or in the phases at which it is applied and removed. Unfortunately the term " error " is in common use for both.

The rate of the pendulum is not directly affected by an impulse given symmetrically about the centre of the swing, even if the impulse be spread over the whole swing. But even with symmetrical impulses, changes in the amount of the force do produce rate errors indirectly through change of amplitude, whilst changes of the phase of application, or removal, cause both direct and indirect rate errors. Apart from temperature effects, errors in the rate of the pendulum may arise from erratic variations in the amount of the driving force, in the positions at which the force is applied and removed, and in the density of the atmosphere surrounding the pendulum. Each of these consists of a direct error which begins simultaneously with the change, and an indirect error which grows gradually (in the course of half an an hour or so) as the amplitude builds up or diminishes to suit the new conditions. According to the circumstances, the direct and indirect errors may have the same sign or opposite signs. It is possible so to select the running amplitude and the phase of application and removal of the force that they balance one another for one particular type of variation, but unfortunately the correct conditions for eliminating one kind of error are quite different from those for either of the other kinds. Hence the correct choice of the running conditions depends upon which source of error is likely to be most important, and this will be different for different types of driving mechanism. The best choice also depends upon the resistance/amplitude characteristics of the pendulum to be used. For instance, with a particular pendulum whose characteristics I have measured, running in air at atmospheric pressure and driven by a force which is reversed at corresponding points in the to and fro swings, the total error due to a small variation of the driving force becomes zero with an amplitude of 140 arc-minutes on each side when the reversal takes place at 100 arc-minutes *after* zero. To eliminate the timing error, the amplitude would have to be raised to 150 arc-minutes and the reversal made at 100 arc-minutes *before* zero. The barometric error would disappear with a running amplitude of 150 arc-minutes combined with a reversal at 50 arc-minutes before zero.

* G. B. Airy: " On the Disturbance of Pendulums and Balances and on the Theory of Escapements," *Transactions of the Cambridge Philosophical Society*, vol. 3, part 1, p. 105 (no date but paper was read on 27th November, 1826).

In each of these cases, any amplitude within certain limits might be selected, provided the appropriate position of reversal was also chosen. These figures are taken from graphs contained in Figs. 55, 59, and 49, of a series of articles which deal with the matter rather fully.*

With the arrangement adopted by the authors (see Fig. 7) the energy given to the pendulum at each impulse is that stored in condenser (45), less some losses incurred in the conversion to mechanical energy. The stored energy varies as the square of the battery voltage and will therefore vary appreciably as the battery runs down. There will also be some variation of the loss in the trigger valve as it ages. It is likely that both of these changes will be too slow to be appreciable, however, during the hour between successive adjustments of the rate. The effects of changes in the permanent current in one winding of magnet (53) may possibly be more important, but presumably they are minimized by keeping the amount of control obtained in this way down to the smallest value which will serve the purpose. Selecting the middle of the swing for the impulse makes the accuracy of the timing a maximum, because there the pendulum is moving fastest. This is a very good reason for selecting that point with this particular method of timing the impulse.

By keeping the amplitude constant within narrow limits the authors lose the partial compensation for the barometric error which would otherwise arise from the fall of amplitude when the barometer goes up. But this could be restored by giving the impulse before zero, where it accelerates the rate. The direct effect of a rise of barometric pressure is to slow the pendulum; but as it also increases the resistance, a greater number of impulses per hour would be required to maintain the standard amplitude, and this greater number would increase the aggregate accelerating effect of impulses given before zero.

The arrangement shown in Fig. 10 requires 20 relays, and 4 cam-driven contacts besides the rotating switch; but of course some of these are required for the changeover from one clock to the other, and some for distinguishing between errors of different magnitudes. An arrangement of mine has 3 relays, 3 cam-controlled contacts for the time test, and 2 magnets (advancing and retarding) on the regulator.† In addition, there are two cam contacts for cutting off the battery except for 5 minutes per day, and three for short-circuiting the Post Office line in accordance with their requirements. This apparatus compares the clock time with the morning signal, it advances or retards the clock by 0·2 sec. and alters the rate by 0·1 sec. per day, but does not alter it when the time signal fails to arrive. An electric chronometer measures the clock error to the nearest 0·01 sec., while the change in the position of the regulator indicates whether the clock was fast or slow. The readings for our records may be taken at any time during the 24 hours between the signals. This arrangement has been running for more than 10 years with practically no trouble except that caused by an occasional reversal of the polarity of the Post Office wires, which prevents the relay on that circuit from locking-in on our battery. After this apparatus had been made and described, a way was found to vary the amount of correction in accordance with the time error found at each test, instead of giving a constant amount of correction. It involves a comparatively small addition to the apparatus we have, but has never been made because the existing gear gives results which are amply good enough. It has, however, been described by the late Mr. A. E. Ball.*

* D. Robertson: "Theory of Pendulums and Escapements," *Horological Journal*, 1928–32, vols. 71–74; in particular, articles 54–60, vol. 72, p. 221; vol. 73, pp. 16, 52, 129, 147; vol. 74, pp. 16, 40.

† D. Robertson: "The Clock and Striking Mechanisms for the Great Bell of the University of Bristol," *Transactions of the Institution of Engineers and Shipbuilders in Scotland*, 1926, vol. 70, p. 244; see also A. E. Ball: *Horological Journal*, 1929, vol. 72, pp. 31 and 64.

* *Horological Journal*, 1930, vol. 72, p. 99.

Dr. E. A. Speight and **Mr. O. W. Gill** (*in reply*): In replying to the various points raised in the discussion it appears best to deal with these roughly in the order in which the relevant parts of the installation are considered in the published paper.

Both the speaking-clock mechanisms are continually running and therefore subject to wear. This is necessary in view of the difficulty in starting up an idle clock and setting it in correct adjustment rapidly in the event of failure of the working clock. The effects of wear are, however, minimized by substantial design and regular maintenance attention.

With the exception of the exciter lamps none of the electrical components is deliberately under-run with the object of increasing its useful life.

It is true that in the advance copies of the paper two condensers were shown in the 3-phase oscillator (item 49, Fig. 7) where one would suffice. These condensers did, in fact, exist in an early experimental model though not in the final circuit. (Fig. 7 has been corrected for the *Journal*.) The individual values, however, were such that, from the a.c. point of view, the two condensers were equivalent to the single condensers shown between the other stages of the oscillator.

It is admitted that there are obvious ways in which the present pendulum could be improved in order more nearly to approach theoretical perfection, but it must be remembered that the functions of the pendulums in the speaking clock are rather different from those of pendulums in clocks which are not subject to hourly resetting. In fact, in view of the known errors of the hourly signal, to which the speaking clock is matched, a perfect pendulum would offer no practical advantage.

The operating potentials of the gasfilled relay (item 39, Fig. 7) are derived from the same source as the charging voltage of the condenser 45 (Fig. 7) in such a manner as to be almost completely self-compensating. The effect of possible variations from normal current in the windings of the magnet 53 (Fig. 7) is reduced by keeping the absolute values to a minimum and by the use of a barretter to stabilize these currents. A careful check of the running of these pendulums has revealed no abnormalities in rate such as might be due to supply-voltage fluctuations. Since the written paper was first submitted the rate has gradually become much more consistent. Cyclic variations are not noticed, and it would therefore appear that the effect of traffic in High Holborn must be very small.

Some degree of automatic compensation for barometric error is achieved, incidentally, by the present method of

maintaining the pendulum amplitude, since, although the driving impulse is symmetrical in duration about the zero position of the pendulum, maximum intensity is reached almost at once, i.e. slightly before zero.

The requirements of constant amplitude of swing and minimum departure from simple harmonic motion during each swing are inherent in the method of driving the mechanism, and the actual frequency of impulsing, assuming constant energy input per impulse, is determined by these factors. Impulsing at or about zero is probably the only simple way of meeting these requirements.

The reasons for the number of relays shown in Fig. 10 are fully explained in the text. The requirements of this portion of the equipment make it unlikely that the same degree of reliability and consistency of operation could be obtained with a circuit requiring fewer relays.

With regard to traffic to the clock, it is of interest to note that the steady increase in the weekly total number of calls is being well maintained, although an appreciable drop occurred during Christmas week. The peak on New Year's Eve was comparatively small.

The question of extending the service to provincial towns is now being actively pursued. As a result of the latest improvements in the characteristics of the main trunk lines, transmission delays have become negligibly small and there is no fundamental technical objection to serving the whole country from the one installation. In view of the popularity of the service, however, it is proposed to construct a duplicate installation, entirely independent of the London clocks, to safeguard the service in the event of a major breakdown involving both of the present units.

The remarks of various contributors on new services which might be added in the future are very interesting. No doubt these possibilities will be reviewed in the light of accumulated experience when the extensions to the present service have been completed.

THE JOINTING AND TERMINATING OF HIGH-VOLTAGE CABLES

By W. HOLTTUM, B.Eng., Member.

[*Paper first received* 1st *May and in final form* 3rd *October*, 1936; *read before the* TRANSMISSION SECTION 9th *December*, 1936, *also before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 4th *January, and before the* NORTH-EASTERN CENTRE 8th *March*, 1937.]

CONTENTS

INTRODUCTION

Apart from the portion of the paper by C. Vernier* referring to the jointing of e.h.t. cables, no paper read before The Institution hitherto has dealt with this subject. It is not proposed to deal in this paper with the jointing of the special types of cable using oil and gas under pressure in various ways, as the basic principles are the same for all. These principles have their simplest application for the straight-type mass-impregnated and pre-impregnated paper-insulated and lead-covered cable, for which they have been developed. It would appear that there will be an extensive field of application for cable of this type for an indefinite period. Some record and discussion of the state of the art at present, when alternative forms of cable are making their appearance, should serve a useful purpose. A study of the subject should be directed to the production of the most reliable designs consistent with economy, as the paramount need for security may otherwise lead to unnecessary expense.

The paper is necessarily concerned mainly with general principles, together with descriptions of some methods of construction, including those which the author believes to be most advantageous. It is hoped that particulars of other constructions, with their advantages, will be given in the discussion.

It may be said that joints and terminations can now be made of an electric strength equivalent to that of the cable. If the combination of cable and joints is stressed to failure, the stressing and the previous history will probably decide which is to be the first to break down.

The following joint-operation record is given not as a testimony to reliability, but as a matter of interest and a possible basis for comparison, present or future. One of the large municipal supply undertakings in this country which had 35 miles of 33-kV 3-core cable in 1924, increasing to about 140 miles in 1935, had 23 joint failures during that period. Of these, 17 occurred with belted cable, although the quantity of this type of cable was much less than half the total quantity in operation. While belted cable is now obsolete for this voltage, it need not be concluded that it was responsible for the large proportion of joint failures. Being the oldest, it probably had the least efficient design of joint, as well as the longest period of operation. Of the remaining 6 failures—3 on screened 3-core cable and 3 on S.L. cable—the cause was attributed to migration of compound in 3 cases, and to defective jointing, leaky joint-sleeve, and ground subsidence in the remainder.

With modern 33-kV 3-core screened cable and joints the earlier records should be greatly improved upon, and in fact failures due to inherent causes have been virtually eliminated.

The technique of the jointing of high-voltage cables is a combination of essential features and of precautions dictated rather by commonsense application of principles than by actual proof of their necessity. These principles have perhaps a more important place in cable jointing than in most engineering work, owing to the large part played by the human factor.

The familiar form of construction consisting of a conductor joint usually surrounded by some form of solid insulation, and enclosed in a compound-filled metal sleeve, forms the basis of all designs. The problem consists in maintaining at the joint the essential characteristics of the cable in the most economical manner possible. These characteristics are conductivity,

* C. VERNIER: "The Laying and Maintenance of Transmission Cables," *Journal I.E.E.*, 1911, vol. 47, p. 313.

insulation resistance, and electric strength. While a construction providing uniformity with the cable might appear to be the ideal, and an approximation to it may be possible by the use of a married joint and the rebuilding of the cable insulation by hand-wrapped paper tape, it is impracticable by reason of the skill and time involved.

The insulation resistance offers no difficulty and could be obtained by the use of one or more of many materials, in conjunction with a sealed container or sleeve which would permanently exclude moisture. The electric strength is the main problem, and the required value is usually achieved by increasing the length of path to earth and introducing laminated solid insulation which, while necessarily inferior in quality to the factory-applied cable insulation, suffices by reason of its greater thickness. For the higher voltages, provision must also be made for the suitable distribution of electric stress. The complete joint is provided with some form of external protection.

The jointing of high-voltage cables involves some physical strain on the jointer due to the length of time—from 6 to 24 hours, broken only by meal times—required. It is not advisable for one jointer to relieve another as the division of work would reduce the jointer's sense of responsibility. It is therefore important to keep the labour of jointing to a minimum, to prevent poor work which might be caused by fatigue.

Generally-accepted voltage limits for cables of the ordinary solid type are 33 kV for 3-core and 66 kV for single-core. The former came into use in 1920 and the latter in 1925. The cores of 33-kV 3-core cables are now always individually screened with copper tape or metallized paper, and 33-kV and 66-kV single-core cable is similarly provided with a screen over the core to short-circuit any space between the cores and the sheath.

The kinds of joints and terminations required for ordinary and special circumstances are illustrated as follows:—

(*a*) Normal joint: Fig. 1 (11 kV, 3-core), Figs. 2 and 3 (33 kV, 3-core), Figs. 4 and 5 (66 kV, single-core), Fig. 6 (22 kV, S.L.).

(*b*) Trifurcating joint, for connecting a 3-core cable to three single-core cables: Fig. 7 (33 kV).

(*c*) Barrier joint, for use on gradients to limit migration of compound: Fig. 8 (33 kV, 3-core), Fig. 9 (66 kV, single-core).

(*d*) Tee joint: Fig. 10 (22 kV, 3-core).

(*e*) Expansion joint, for use in subsidence areas: Fig. 11 (22 kV, 3-core).

(*f*) Outdoor terminal box: Fig. 12 (22 kV).

(*g*) Indoor terminal box: Fig. 13 (11 kV).

(*h*) Outdoor sealing-end: Fig. 15 (66 kV).

(*j*) Indoor sealing-end.

(2) JOINT DESIGN AND CONSTRUCTION

The requirements of a satisfactory joint design are, in chronological order: (A) Economy in cost of materials. (B) Economy in installation cost. (C) Speed of installation. (D) Satisfactory operation.

The consideration of each individual part of a joint may be allowed to fall into four sections:—

(i) The special characteristics required.
(ii) Considerations bearing on the design.
(iii) The construction usually followed.
(iv) The jointing processes involved. (This section will only be dealt with in regard to special points.)

In what follows the individual parts will be dealt with in jointing sequence.

It may be remarked that the word "joint" is much overworked in dealing with this subject, being used to denote the complete assembly, the conductor joint, or a joint between parts of the sleeve. Qualifications must therefore sometimes be made to prevent ambiguity.

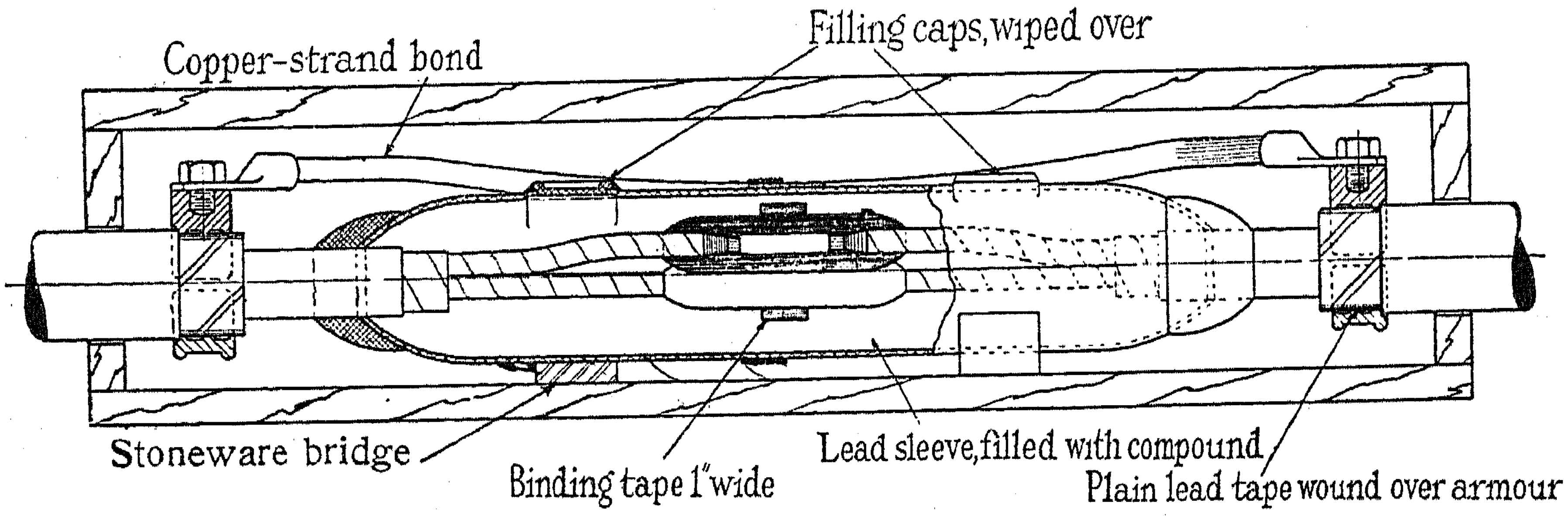

Fig. 1.—11-kV 3-core normal joint.

(a) The Conductor Joint

(i) The special characteristics required are conductivity, mechanical strength, and freedom from surface irregularities which would cause concentration of stress.

(ii) Compressive stress due to expansion of the conductors is the normal operating condition, and requires no special provision. Creeping on gradients or ground subsidence may give rise to tensile stresses, and failures will be minimized if strength is provided to resist these. In a joint made by soldering each conductor to a third member (ferrule or braid), a minimum length is required to give maximum strength. Under tension the conductor will stretch more than its attachment and break away gradually, so that extra length would only be wasteful.

(iii) Ferrule joints are most usual, and are of three types: First, the plain tube split along the top. Second, the "grip on" type, which has a weak section opposite the split and is closed on to the conductors, thus avoiding bending the cores for insertion as in the first type (see,

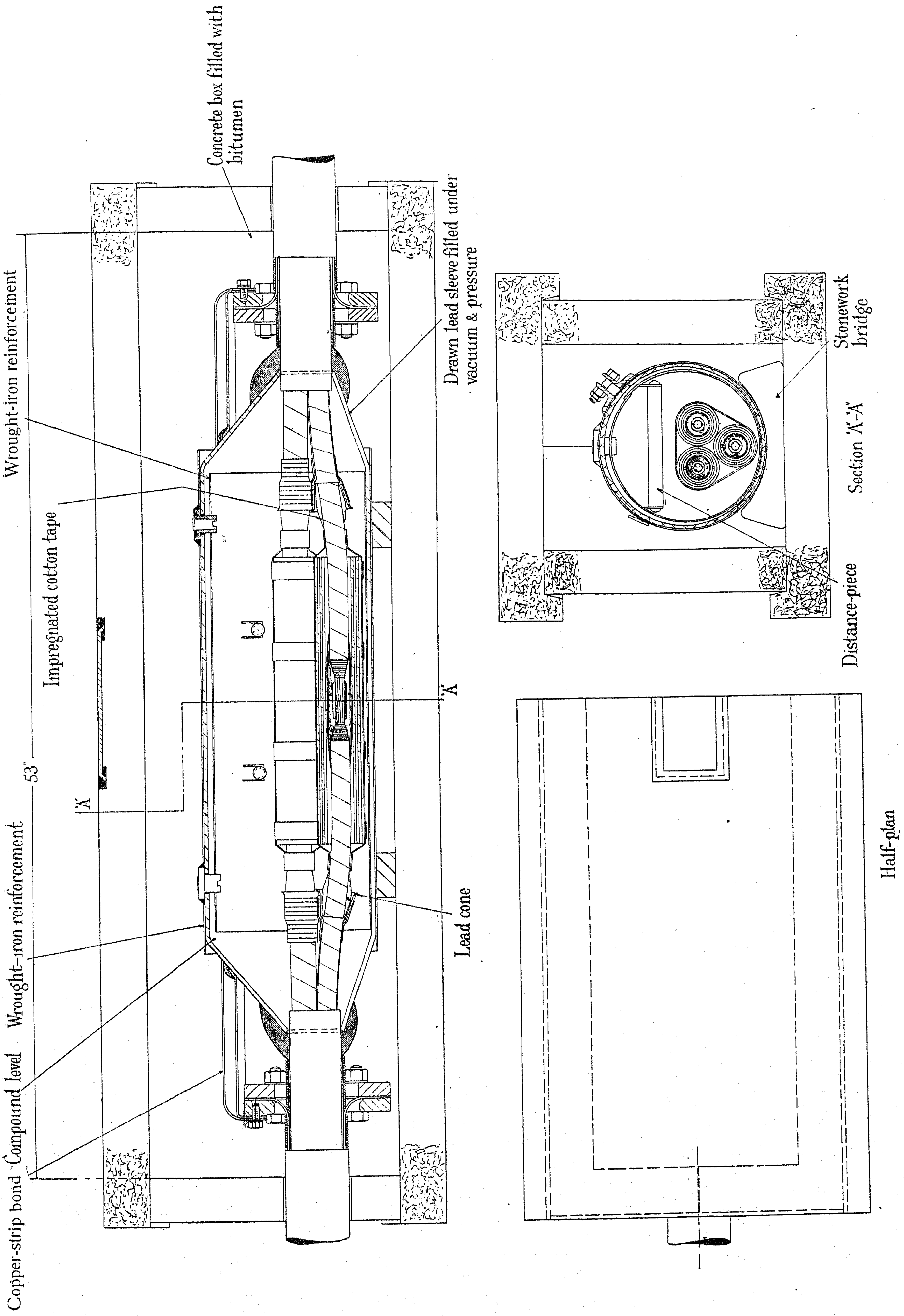

Fig. 2.—33-kV 3-core normal joint.

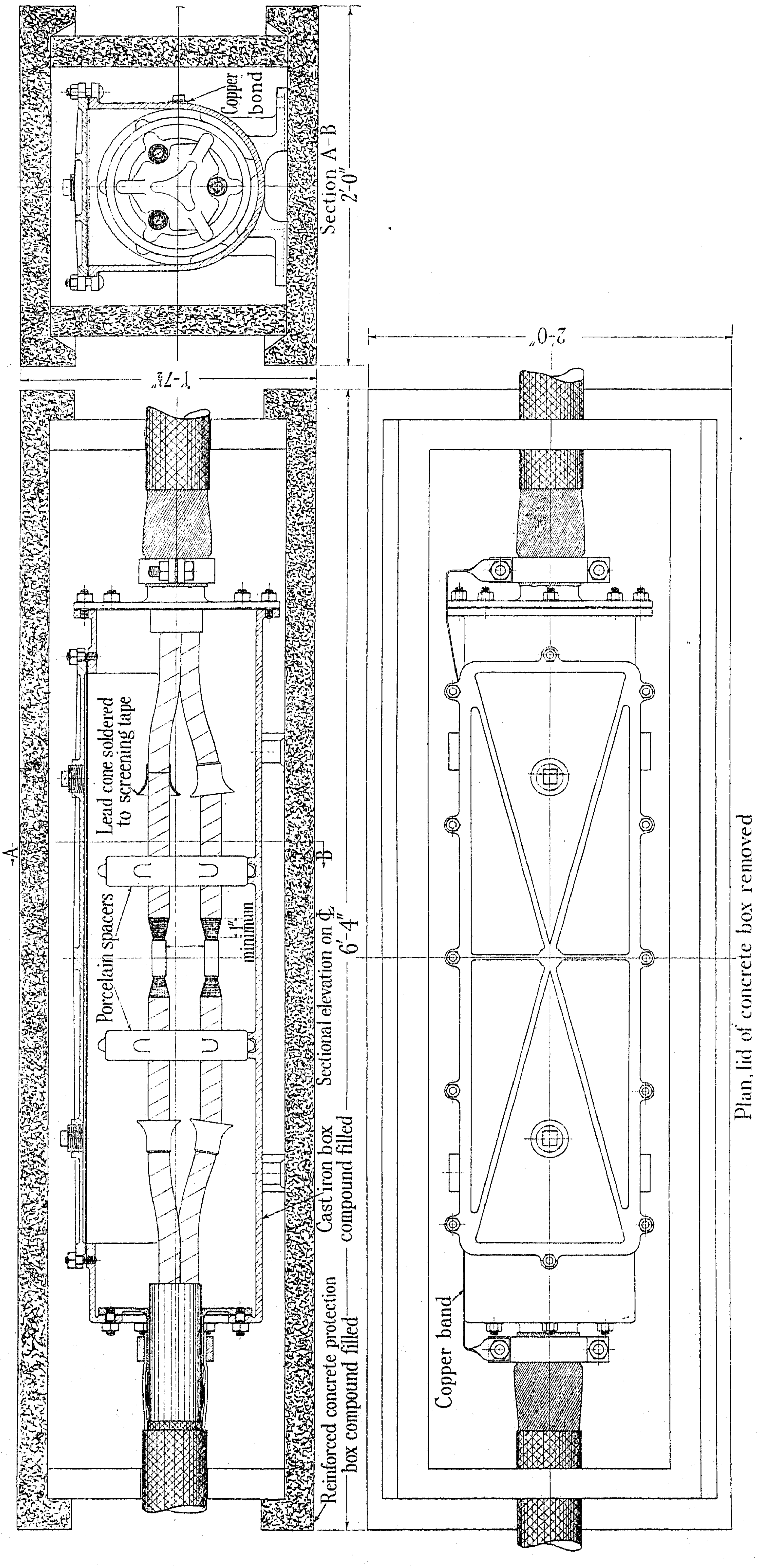

Fig. 3.—33-kV 3-core normal joint.

for example, Fig. 4). Third, forms of built-up ferrules, designed to avoid bending the cores. Ferrules generally vary in length from about 7 times the conductor diameter for the smallest sizes, to 3·3 times for the largest.

Copper braid joints* are still used to a considerable extent (see Fig. 7), and telescope joints may be used occasionally. Braid joints consist of pieces of woven copper braid made with wire about 0·006 in. diameter, a sufficient number of pieces being laid along the butted ends to surround them, and bound with tinned copper wire and well soldered. The length is from about $2\frac{1}{2}$ in. to 5 in. and the section per braid from about 0·003 sq. in. to 0·1 sq. in. In telescope joints each layer of wires is cut to a different length so that the layers butt in different planes, the joint being secured with a layer of tinned copper wire and soldered. A method of jointing conductors by welding has been used in Germany, but it seems questionable whether any advantages it may have would justify the cost of the plant.

(iv) No attempt should be made to connect the cores of high-voltage cables colour to colour unless the colours come opposite, or unless a specially long sleeve is provided. Should the rotation of colours be opposite a cross would be necessary to keep colour to colour. This would require a fatter and longer sleeve, and, in any case, crossing is undesirable for voltages above 11 kV.

For all kinds of joints except the married and telescope types the conductor ends are first tinned, and after assembly the joint is well basted with solder, usually 2 parts tin to 1 part lead. There is no difficulty in using ferrules on shaped conductors if the bared portion is first squeezed circular with gas pliers.

In braid joints the braids are cut to a taper at the ends, to smooth the contour. The wire binding must start from the conductor, or it will slip on the taper. Ends of braid wire therefore tend to project, and any such must be removed when smoothing is carried out after soldering.

For all joints, the cable insulation is first left at about $\frac{1}{8}$ in. from the conductor joint, and after soldering is cut back about $\frac{1}{8}$ in. to remove any scorched surface, and tapered to receive the wrapped-on insulation. A radial surface would form a plane of cleavage parallel to the stress lines.

(b) The Insulation

By this is meant any solid or wrapped-on insulation, as distinct from the compound filling. The compound alone is sometimes relied on to provide all the insulation necessary. Fig. 3 shows a 33-kV normal joint which has given satisfaction on pre-impregnated cable, and is insulated only by the hard-setting compound filling. The author is of opinion that with fluid compound this construction is liable to give less certain results, owing to minute irregularities of the conducting surfaces, combined with voltage surges which may occur on any system.

(i) The special characteristics required are high electric strength, high insulation resistance, and freedom from occluded air or vacuous spaces.

(ii) The strongest known form of insulation applicable consists of a solid mass completely enclosing and in close contact with the conductor, built up of close-fibred material in laminations normal to the direction of stress, and with all interstices filled as completely as practicable with a suitable insulating fluid. Paper is the material which most suitably combines the close-fibred structure required for the strength of the individual laminations with a degree of porosity which will admit of impregnation after wrapping. Insulation applied under jointing conditions, whether by hand or by machine, is inevitably inferior to the factory-applied insulation of the cable. This inferiority consists in slackness, irregularity, the presence of air and minute traces of moisture, and incomplete impregnation. By increasing the dimensions over those of the cable, however, these features are compensated for. Paper tape is much stronger electrically than cotton, but is more fragile to handle, and can only be neatly wrapped on parallel surfaces. Cotton tape is therefore preferable where the electric strength of paper is not called for, and may be used up to 22 kV. From 22 kV upwards, the bulk of insulation required is such that the time involved for insulating by tape wrapping only can be materially reduced by the use of impregnated paper tubes.

(iii) The insulating materials usually used in joints are cotton tape, paper tape, and paper tubes, impregnated and packed in sealed tins in compound, which may with advantage be of the kind used for the joint filling. Up to 11 kV the applied insulation is generally impregnated cotton tape only (see Fig. 1). From 22 kV upwards paper tubes, either alone or in combination with a tape wrapping, are usual. If unsupported by an internal wrapping of tape the tube is usually centralized on the conductor, e.g. by an ebonite spider at each end.

Paper tubes may be made either in one piece or in four concentric sections split longitudinally, and assembled with the splits equally spaced circumferentially. While one-piece tubes are better electrically, their use on 3-core joints requires a longer sleeve to give sufficient length of core to accommodate the tubes while the conductors are being jointed. Split tubes are found satisfactory up to 33 kV and are frequently used from 22 kV to 33 kV in 3-core joints, and also in single-core joints where one-piece tubes are inconvenient. Split tubes are used in the joints shown in Figs. 2, 6, 7, and 8.

With regard to the taping in the space between the paper tube and the cable core, a large number of 66-kV joints have given satisfactory service where the whole of this is of impregnated cotton. Above 22 kV it is now usual to use paper tape, but, as it is difficult to make a satisfactory job with paper in the end spaces up to the diameter of the conductor joint, cotton is usually retained for this part. The taping should extend an inch or more on to the parallel core insulation beyond the taper. One or two layers of impregnated cotton tape are sometimes put on over all exposed cable-core insulation. This is a practice for which it is difficult to find adequate reason, and it may be regarded as preferable to leave the paper surface exposed to fluid compound.

The insulated cores of 3-core joints are usually surrounded by a tape binding, and may or may not be separated by some form of solid spacer (see Figs. 1, 2, and 3).

Provision is generally made to register the position of

* British Patent No. 15413—1909.

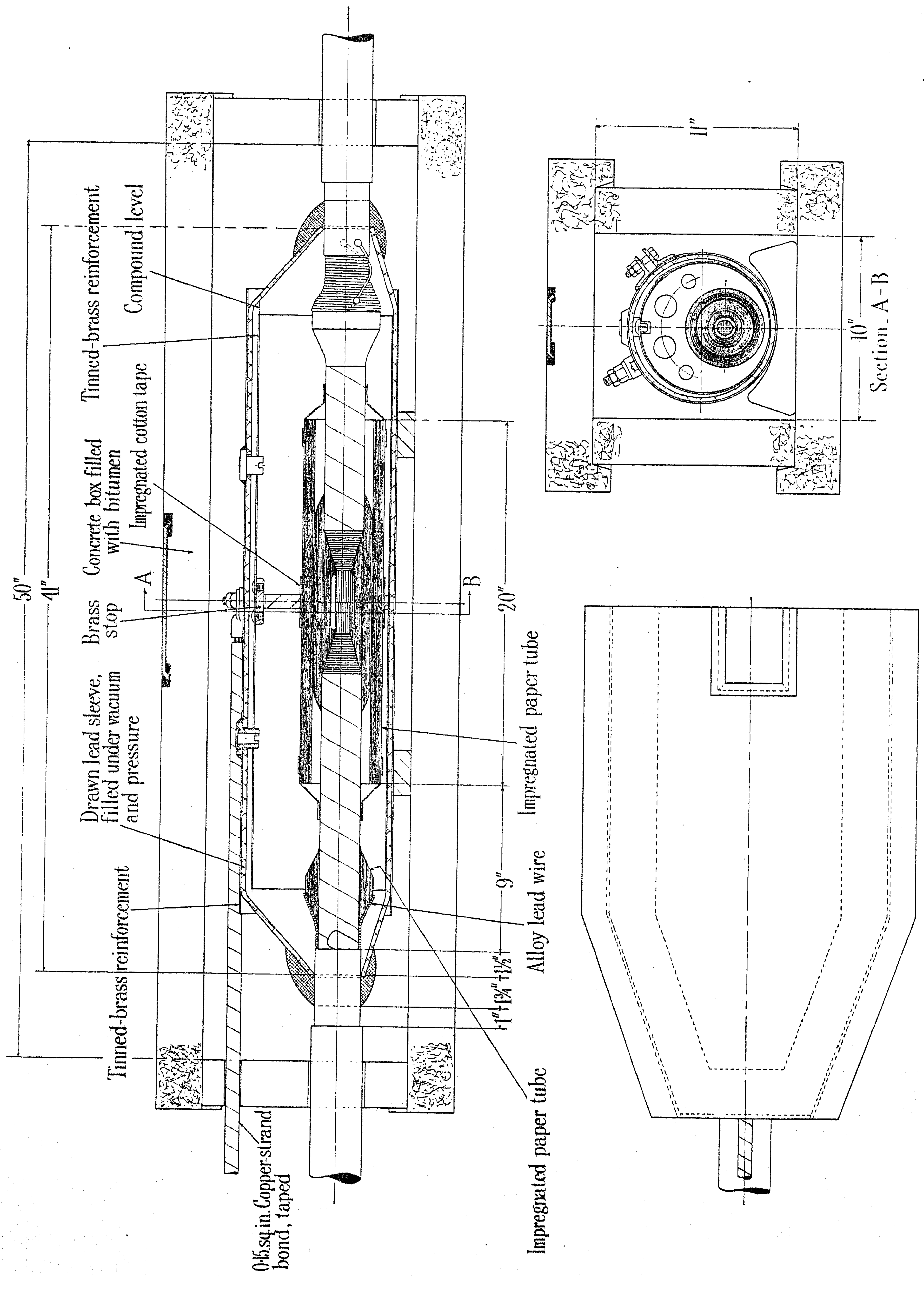

Fig. 4.—66-kV single-core normal joint.

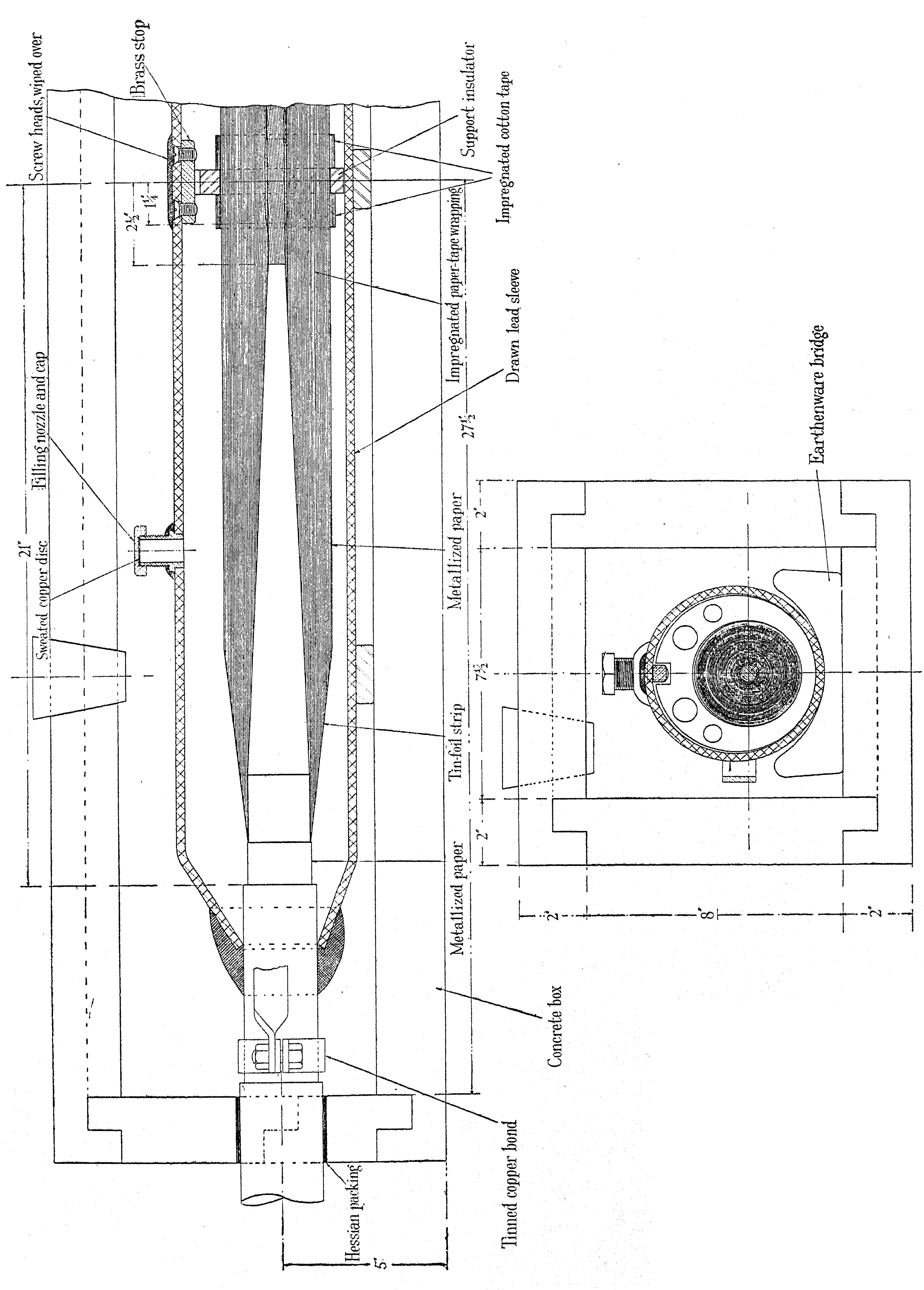

Fig. 5.—66-kV single-core normal joint.

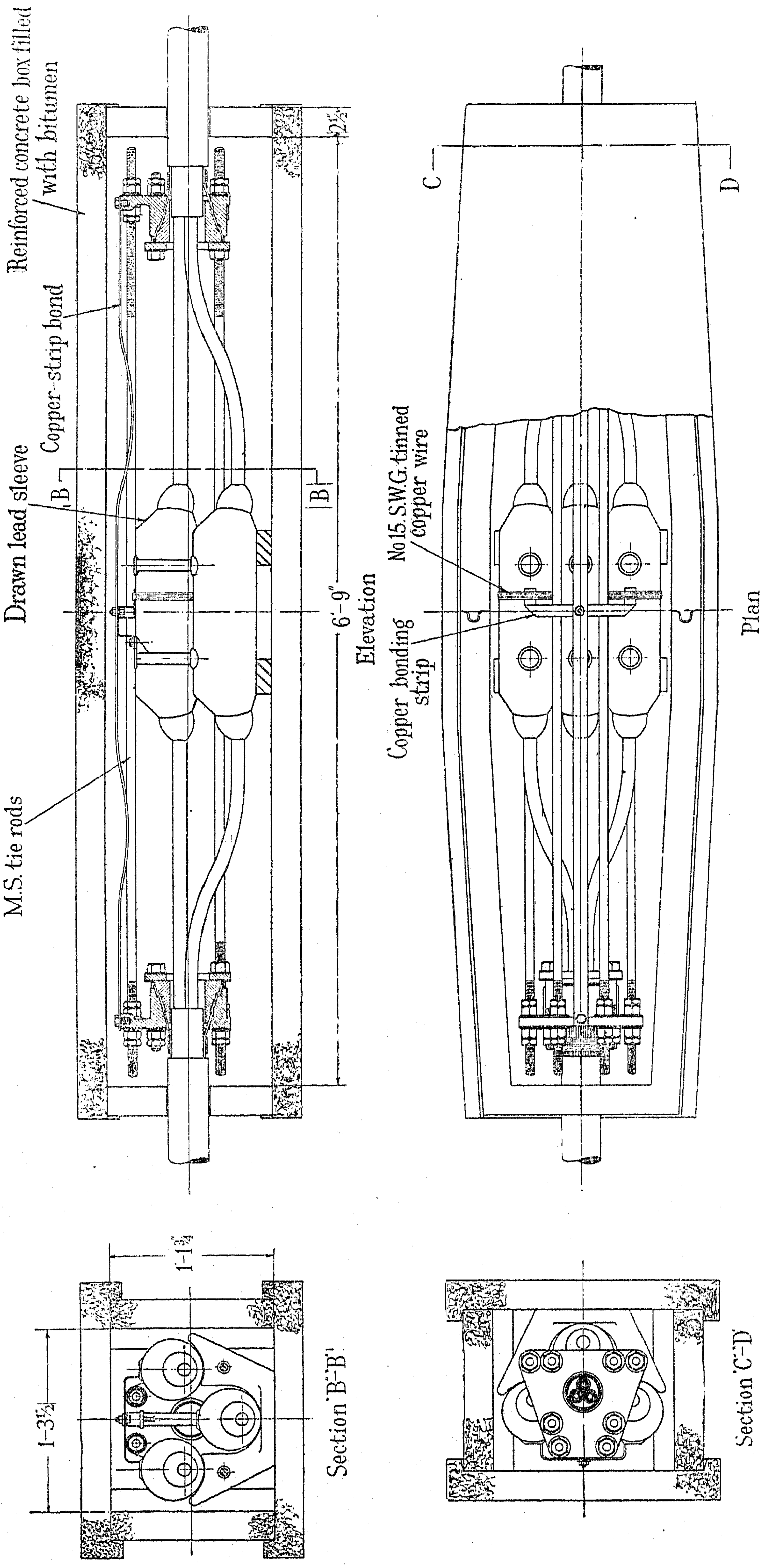

Fig. 6.—Normal joint on 22-kV S.L. cable.

the core or cores in the cross-section of the sleeve. A thick binding of tape may serve this purpose, or a piece or pieces of porcelain or moulded insulation may be either attached by tape to the insulated cores or attached to the sleeve (see Figs. 1, 2, 3, 4, 5, 6, and 7).

(iv) The strictest precautions against moisture are essential, and all jointing materials in addition to being supplied in sealed containers should be tested for moisture on site. There are two usual methods in regard to compound and materials supplied in compound. First, to heat the compound with any contained materials to a temperature of about 110° C.; and second, the "hot wire" test, carried out by plunging a red- or white-hot spiral of wire into a sample of compound. By either method moisture is indicated by a crackling sound, and if the moisture is not excessive it may be removed by maintaining the materials at 110° C.

In the process of applying impregnated tape, tightness, uniformity, and freedom from moisture and spaces, are aimed at. Basting is frequently advocated as a means of ensuring freedom from moisture. Basting each layer with gradually-cooling compound would no doubt be beneficial, but would take a prohibitive time. Basting tends to drain the surface layers, on account of the fluidity of the compound at the temperature necessary to make it of use as a drying process. Hence, and also because of the contraction resulting from the high temperature, spaces are likely to result. Moisture from the atmosphere and the jointer's hands results only in very minute deposits, and moreover the latter will be much reduced by taping cold. It may be claimed that the cold wrapping of impregnated tape, each roll being lifted from cold compound immediately before use, and cold compound being smeared on each layer applied, will result in the occlusion of a negligible amount of moisture and a minimum of air. Lengthy experience of this method provides no evidence to the contrary. Above 11 kV it is usual to protect the cores from the atmosphere during jointing by a layer of impregnated cotton tape, removed just before closing the joint. An equally effective and more economical way is to remove two layers of paper.

(c) Stress Control

(i) Owing to the different diameters of the surrounding earthed surfaces, concentrations of stress may occur, and provision must be made to ensure that these are not excessive.

(ii) The only points and voltages in question are at the terminations of the sheath or screens from 33 kV upwards. Cables of these voltages, both single-core and 3-core, now usually have a conducting layer over the insulation of each core, so that the problem consists in suitably disposing of these screens. The most uniform stress distribution would be obtained by making the screens continuous through the joint, with as gradual changes of diameter as possible. As screening is less necessary in a joint than in the cable on account of the reduction of stress caused by the separation of the cores, the advantage of continuous screening lies only in the avoidance of terminations. On the other hand, it is laborious to construct, may prevent free access of compound to the insulation, and will act as a conductor between the weakest places in the insulation of each core. It is therefore more usual to terminate the screens short of the applied insulation. The concentration of stress is dealt with by fitting some form of bell mouth, usually termed a "stress cone." A cone which is filled with fabric insulation is found to give much greater strength than one having compound only between the cone and the core insulation.

(iii) Where the screen is made continuous, the insulation is built up, usually with paper tape or a paper roll, to a long tapered formation, which is then covered with a conducting layer. This may be formed of a metallized-paper wrapping over the parallel portion, and tinfoil in the form of stretchable tape or shaped pieces on the conical portions (see Fig. 5).

For 3-core cable, a convenient form of stress cone consists of a lead bell of which the narrow end is slotted to form gussets about $\frac{1}{4}$ in. wide. This is centralized and supported by a conical "buffer" of impregnated cotton tape, the end of the screen being brought beneath the slotted end of the bell, the gussets being closed on it and the buffer, and secured with a tape binding (see Figs. 2, 7, and 8). On single-core cables either the same form of stress cone may be used, or else one consisting of $\frac{1}{8}$-in. diameter lead-alloy wire wrapped on a paper-tube buffer. Lead alloy is preferable to pure lead, which can easily be broken, or roughened by stretching (see Figs. 4 and 9). In the case shown in Fig. 3 the stress cones have no buffer, but solid compound is used.

(iv) The buffer is applied in such a direction as to tighten the cable insulation, but not so tightly as to distort it. The lead wire is applied in the same direction as the end of the screen, which terminates under it. The start of the wire is soldered to the sheath, and the end to the turn beside it.

(d) The Joint Sleeve

(i) Watertightness is the outstanding special feature required.

Sections (ii) and (iii) are in this case best combined. The function of the sleeve is to exclude moisture, and to keep the joint immersed in compound. Above 11 kV, and sometimes from 11 kV downwards, a fluid compound is commonly used, which tends to a limited extent to be absorbed by the cable. Some manufacturers endeavour to prevent this absorption as far as possible by means of oil-proof wrappings over the end of the cable sheath. On the other hand, the uniformity of the cable impregnation will be disturbed by the heat of making the plumbed wipes which unite the sleeve to the sheath, and percolation of the joint compound can be utilized to restore the original impregnation. Freedom of access of the joint compound to the cable may eventually result in migration of a material portion. Capacity for surplus compound must therefore be provided either in the sleeve or in a container attached to it, the former being the cheaper and more convenient method. The amount of migration cannot be predicted and will depend on the gradient in each direction, the fullness of impregnation, the tightness of the cable-sheath and insulation, the operating temperatures, and the viscosity of the cable and joint compounds. A logical and effective rule is to make the

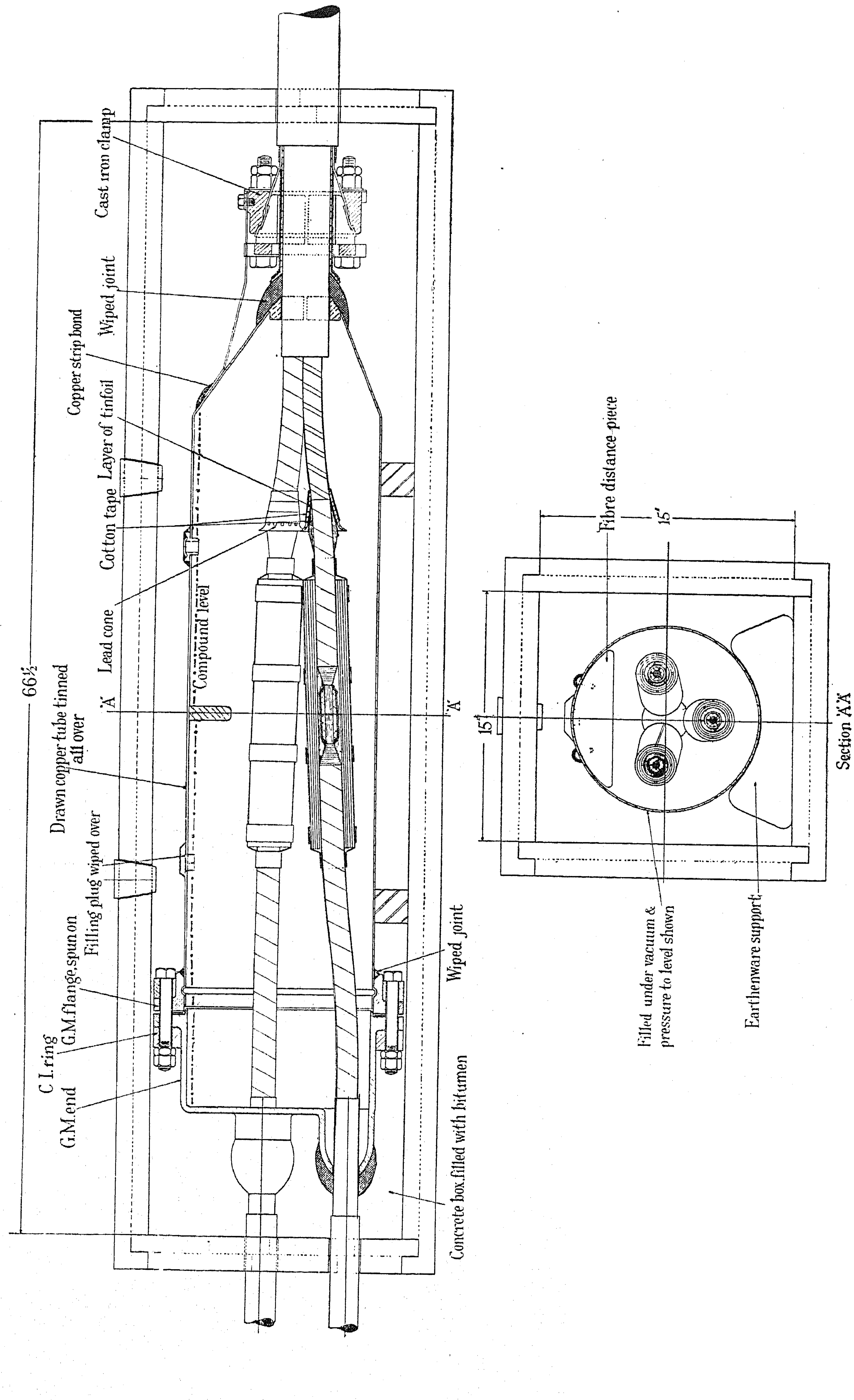

Fig. 7.—33-kV trifurcating joint.

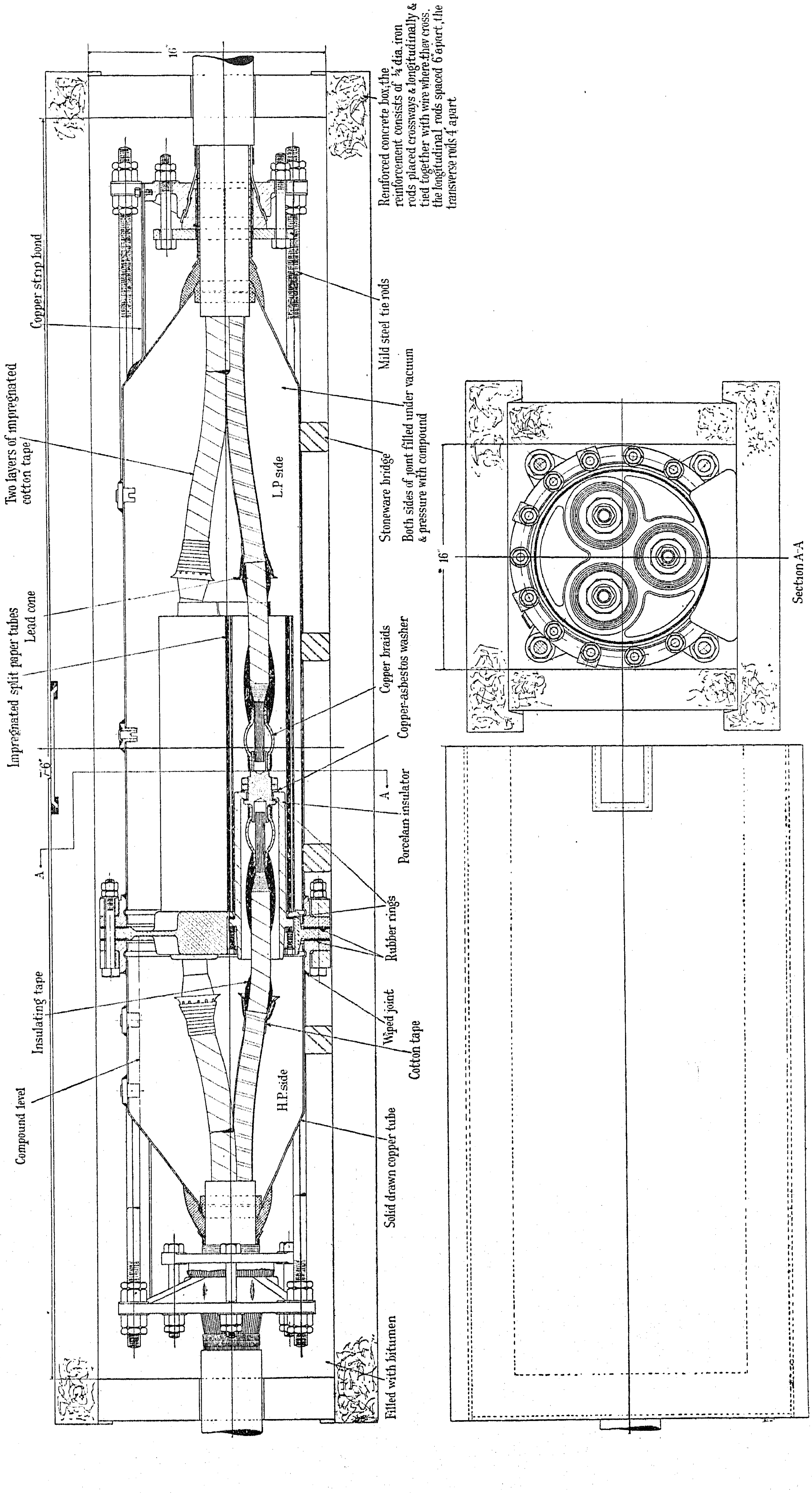

Fig. 8.—33-kV 3-core barrier joint.

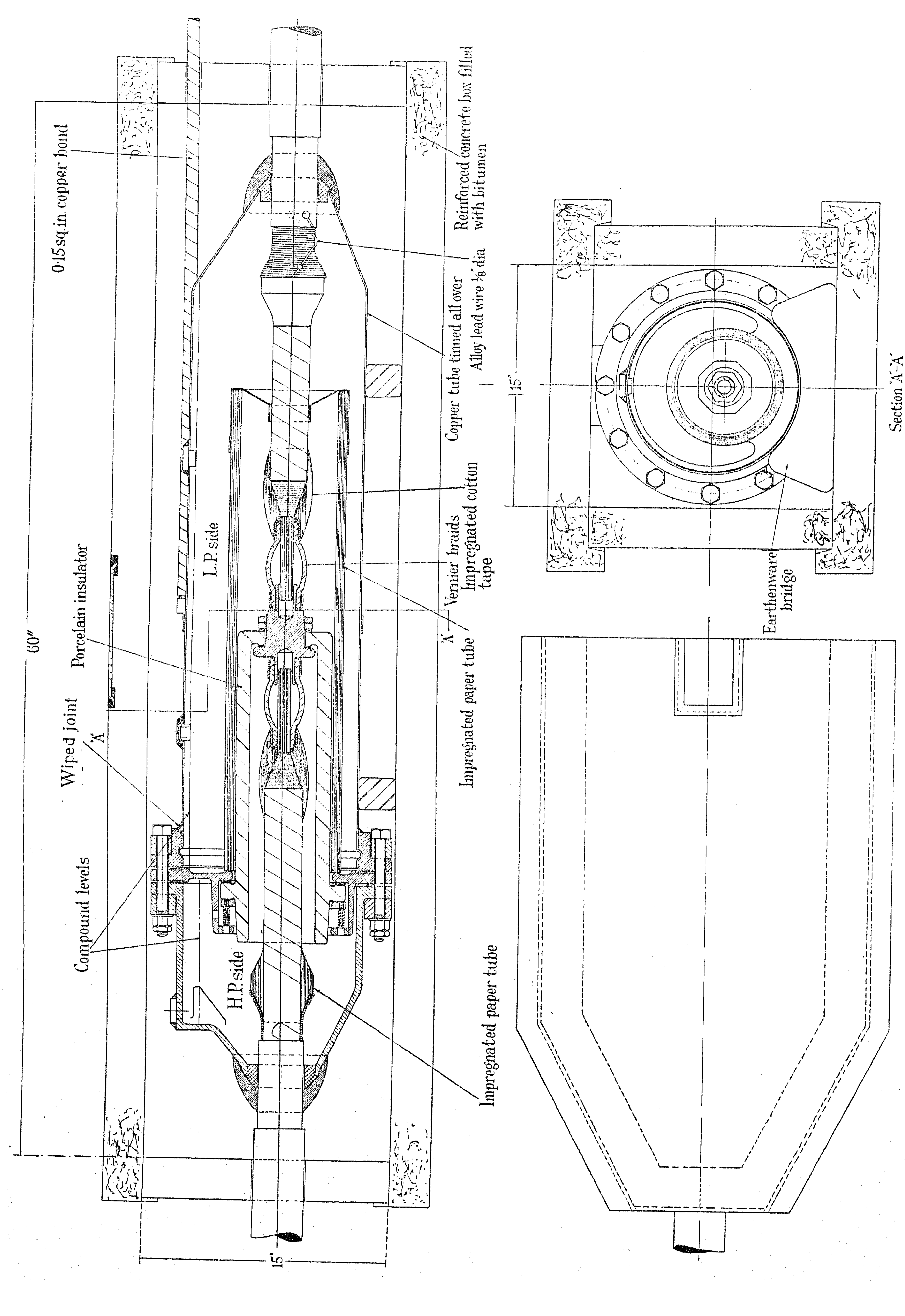

Fig. 9.—66-kV single-core barrier joint.

sleeve of such dimensions that the surplus compound, or reservoir capacity, is a definite fraction, say $\frac{1}{60}$, of the volume occupied by the paper and compound in the cable-length between adjacent joints. It is usual also to leave a small air space, which may be about $\frac{1}{400}$ of the cable paper and compound volume, to prevent the development of excessive pressures due to expansion. For the smaller sleeves, of 11 kV and less, reservoir capacity is not always provided, as in these cases the cable has a more viscous or hard-setting compound. The sleeve is united to the cable sheath by plumbed wipes.

The simplest form of sleeve is the drawn lead sleeve with ends beaten down to the cable diameter after jointing. This type is also the most reliably watertight. It is universally used for the smaller joints and lower voltages, and can be used for all normal and expansion joints, but is not applicable to barrier and trifurcating joints. For the larger sizes it has the disadvantages of lack of rigidity, and of the labour required in dressing down the ends. The former may be overcome by sheet-metal internal and external reinforcements,* which will enable vacuum or pressure to be withstood (see Figs. 2 and 4). Another form of reinforcement makes use of iron bands. The dressing of the ends may be eased by warming with a blowlamp. It may be claimed that the drawn lead sleeve applied in this way makes the most satisfactory job for all cases where it can be used.

A modified construction of the ends of drawn lead sleeves makes use of lead bushes on to which the sleeve ends are dressed, thus reducing the amount of dressing required. This results in much larger wipes. For any form of sleeve the ends are made of lead, brass, or copper, in order to provide a suitable wiping surface. Where the body of the sleeve is not of lead, brass is usually used for the ends, unless the sleeve is of copper.

Alternatives to the drawn lead sleeve are cast lead, with or without incorporated reinforcing bands, drawn copper, and cast iron. As in these cases it is not possible to dress down the ends, they must be large enough to pass over any outer coverings of the cable, the annular spaces being closed by split lead bushes. Such sleeves must be made in at least two parts, usually with a circumferential joint, one part being placed on each cable-end during jointing. In the case of cast lead the joint will be plumbed, for drawn copper it may either be plumbed or provided with flanges and bolted, and for iron it will be bolted. Copper sleeves are shown in Figs. 7, 8, and 9, and an iron sleeve in Fig. 3.

Flanged joints should preferably be avoided where the joint is either buried or may become immersed, on account of possible ingress of moisture; where found necessary, a well-designed joint and a protection box filled with a flexible bitumen should be employed.

An air-pressure test under water is frequently carried out in the factory on any kind of built-up sleeve, as a check on the design and materials. This is much more searching than a test by liquid pressure.

Fig. 3 shows an iron-sleeve type of 33-kV 3-core joint which is extensively used. The left-hand end-plate slides inside the sleeve as it is moved up the cable. The top plate is put on after the hard-setting compound has been poured in, and the two screw plug-holes are used for topping up after cooling.

For trifurcating joints the 3-core end may consist of an iron casting with a brass gland bolted on, or of a drawn copper sleeve with coned end; and for the single-core end an iron casting with glands bolted on may be employed, or a brass casting having glands integral with it. (See Fig. 7 for an example of a copper sleeve.)

Oil-resisting rubbers are now available as jointing-ring material, and these have greater resilience than other jointing materials such as compressed paper or cork. Rubbers can be obtained of different degrees of hardness which will withstand immersion in oil or compound at 100° C. for 2 weeks or more with negligible dissolution. Samples $\frac{3}{32}$ in. thick may expand 100 per cent or more in this time, but in practice the edge only is exposed to the filling medium, and any expansion will tighten the joint. Under normal conditions of use where the maximum temperature is much below 100° C., and only the edge exposed, the life of these rubbers may be regarded as practically unlimited.

(iv) The question of the assembly of the sleeve on site calls for no comment. It would be of interest, however, if contributors to the discussion would give their opinions of the relative merits of pot and stick wiping, and of the various grades of plumbing metal.

(e) The Filling Compound

Hard-setting compound is found satisfactory up to 33 kV for pre-impregnated cables, but a viscous fluid compound is usual for mass-impregnated cables above 11 kV, and is frequently used from 11 kV downwards. What follows refers particularly to fluid compounds, and therefore to the higher voltages.

(i) The filling compound must be (α) homogeneous, and permanently stable under the electric stress. (β) The viscosity must be high enough to prevent excessive drainage into the cable, and low enough to allow penetration of the applied insulation, and to prevent spaces developing with expansion and contraction. Such a compound will also have the essential quality of being incapable of forming contraction cavities. (γ) While insulating compounds in general have adequate insulation resistance and electric strength, in addition the power factor of the compound at working temperatures must be low enough to avoid electrical instability. (δ) The compound must be miscible with the compound in the cable without harm. (ϵ) The compound must be uninjured by heating sufficiently to ensure dryness, and to make it fluid enough to permeate the joint insulation.

(ii) The advantages of filling a joint with compound, as against relying on applied solid insulation alone, are as follows: (α) The electric strength is increased by the percolation of the compound into the insulation, which may eventually become completely filled. (β) The electric strength is also increased by the greater uniformity of dielectric constant. (γ) Residual air and traces of moisture tend to become dissolved and dissipated throughout the compound, and so made less harmful. (δ) The ingress of moisture through any minute leak in the sleeve is greatly reduced or prevented. If the joint is enclosed in bitumen, however,

* British Patents Nos. 234224—1924 and 228304—1923.

this will be a more effective seal. (ϵ) Drainage of compound from the cable into the joint is prevented, and local loss of compound from the cable due to the heat of wiping will be made good.

(iii) A good and simple way of meeting the points under (i) is to use compound identical with that in the cable. Some cable makers hold the view that a higher viscosity is desirable in the joint than in the cable compound. The compound is a mixture of mineral oil and resin, the amount of resin depending on the oil viscosity and on the viscosity required in the compound. In joint-filling compounds the resin content usually varies between 20 per cent and 70 per cent by weight of the compound.

A new principle has recently been developed in joint-filling. Styrene, which is a special hydrocarbon, is used mixed with a common solvent of itself and cable compound, and it is claimed that the mixture has great penetrative power, and results in welding the applied insulation to the cable insulation so that the dividing surface is eliminated. The compound thickens during heating, and finally solidifies. A small diameter of joint can thus be used, and it has the advantage of forming a barrier to the flow of compound. Electric strength greater than that of the cable is claimed. It may be questioned, however, whether the cable at the wipe is properly replenished, and whether harmful migration on the lower side of joints on gradients may not occur.

(iv) From 20 kV upward there is some advantage in employing a process of filling under vacuum. Such a process was described in 1911,* and in its modern form is much used. The joint sleeve has two orifices, and a vacuum pump is connected to one and the compound supply to the other. After vacuum has been maintained for, say, 15 minutes the compound is admitted. It is usual then to apply pressure to the compound during cooling and for a few hours after. A hand-operated pump may be used, which can be connected to give either vacuum or pressure. The advantages of vacuum are that it provides a test for leaks, and removes air from the more inaccessible parts of the insulation which would otherwise remain immersed in the compound. On account of the air space which must be left in the sleeve, and the slight imperfections of the cable impregnation which are unavoidable with viscous cable compound, it is not considered that a very high degree of vacuum is called for. A vacuum within an inch or so of perfect will remove a high percentage of the accessible air, and it may be assumed that the remainder will in time dissolve. The admission of the compound to the evacuated joint has a partial degasifying effect which increases the capacity of the compound for air, and the dissolving of residual air probably continues for some time, and is accelerated by the greater mobility of the compound when warmed in service.

The application of pressure to the compound produces more thorough filling of the insulation, accelerates the solution of residual air, helps to restore complete impregnation of the cable at the wipe, and, by penetrating along the cable, tends to reduce any subsequent migration. The pressure is applied through the medium of air, the sleeve being first completely filled. Objection has been raised to the application of air pressure, as being a reversal of the vacuum process. The contradiction is only an apparent one as, the joint being filled, air cannot gain access to the insulation, the only effect being the saturation with air of the surface layer of compound. There is no evidence that this is harmful, and it may be beneficial by tending to prevent the development of vacuum in service. The amount of atmospheric moisture introduced is negligible.

* *Electrician*, 1911, vol. 66, p. 962.

(f) Armour Clamps

(i) These terminate and provide a bonding connection to the ends of the armour, and, where wire armouring is employed in subsidence areas, secure the armour to tie-rods across the joint to enable it to sustain tension.

(ii) and (iii). For steel-tape armour, a collar-type clamp formed of two semicircular parts bolted together is usual. For wire armour the same construction is sometimes used, but an iron-ring support beneath the wire ends is desirable to provide a support on which to clamp. It is more usual to bend out the wire ends and clamp them between two members at a larger radius, using either two flat rings or a cone-type clamp. The stepped-cone clamp ensures contact with each individual wire, and forms a secure mechanical grip where tension is to be sustained. Where a brass gland is used the wires are usually laid over the wipe and clamped to the parallel portion of the gland. Generally it may be said that where tensioning is not required a collar-type clamp inside the protection box is the cheapest efficient construction (see Fig. 1). Where tie rods are required, the clamps are provided with projections to take the screwed ends of the rods. The rods are enclosed with the armour clamps in the protection box (see Figs. 8 and 11).

(iv) Where the armour is required to sustain tension, an initial tension must be provided so that any strain is taken immediately, and kept off the cable. This tension should not be so great as to produce a thrust against the wipes. No positive method of checking the correctness of the tension appears to be available. Observation of the wires immediately behind the clamp provides some guidance, but suggestions for a better method would be useful.

(g) External Protection

(i) The special characteristics required are protection from mechanical damage, protection of metal parts from corrosion, and, in the case of buried joints, additional waterproofing as a protection against any possible leak in the sleeve.

(ii) and (iii). Joints not buried in the ground but installed in pits, subways, etc., are generally assumed not to require additional protection. For buried joints the protection is required to be able to withstand a blow from a pick. For waterproofing and sealing of leaks a plastic compound insoluble in water is indicated. A robust box filled with bitumen is the obvious method of meeting these conditions, and is usually employed. As the box cannot easily be made fluid-tight the bitumen must be hard enough not to flow from joints in the box at the

highest temperatures which may occur, and, in view of its high expansion coefficient, must be soft enough not to crack at the lowest temperatures and thus admit moisture. A bitumen having a penetration value of about 65 is found to be suitable. The protection box may be made of creosoted timber, with an iron plate over the lid, or of reinforced concrete. The latter is now the usual construction, though wood boxes have been found in sound condition after 20 years in the ground. The box is usually made in several pieces for convenience in handling, as for the largest joints its weight may approach 1 ton.

The mass of bitumen has a blanketing effect, and with continuous loading the temperature of the interior of the joint may exceed that of the cable. It is now recognized that fluid-filled joints can withstand a higher temperature than the cable, as any voids tending to occur on cooling will be made up by the compound in the sleeve.

Sand filling of protection boxes has been and is still employed to some extent, and probably originated with the idea of reducing the joint temperature. It has persisted on account of the easier access to the joint in case of breakdown or for examination of compound level, and the lower cost. Against this must be placed the disadvantage that the corrodible parts must be well painted if sand filling is employed, and, in view of the improbability of access being required, it may be claimed that the protection from corrosion and leakage provided by bitumen is well worth while.

(iv) The protection box must be on a firm foundation so that settlement, which would put a strain on the wipes, cannot occur. In soft ground it is advisable to support heavy joints on a concrete raft. Before filling, the joints in the box should be sealed with clay. For large sleeves one filling orifice should be undone to prevent excessive pressure due to heating of the joint sleeve. The bitumen is then put in nearly up to the open orifice, which is sealed after cooling. The effect of such pressures might be to distend the sleeve or to force compound into the cable, so that after cooling the level would be reduced. After sealing, the filling is completed and the box closed.

(h) Bonding and Earthing

The bonding required is as follows: (i) Between the sheaths of jointed cable-lengths. (The joint sleeve is usually an effective bond.) (ii) Between the armouring of jointed cable-lengths. (The connection is made to the armour clamps.) (iii) Between the armouring and the cable sheath. (The connection is usually made from the armour clamps to the joint sleeve.) (iv) Between the sheaths of three single-core cables forming a 3-phase feeder. (v) Between two or more feeders laid in one trench. (This type of bonding has not always been carried out, but seems to be growing in favour.)

A usual size of bond is 0·15 sq. in. This size is usually chosen irrespective of the size of the cable conductor. A robust connection is essential, as the bond frequently lies in the ground with no protection but a tape wrapping. The 0·15-sq. in. size also suffices to meet all electrical requirements.

No general rules for earthing can be laid down, as supply authorities frequently have their own views. On some of the cables installed by the Central Electricity Board in London, where two or more feeders run together an earth plate has been installed at each joint position, connected through a link box to the joint bonds so that the earth may be connected or not according to the state of the earth potential.

(3) NOTES ON PARTICULAR TYPES OF JOINTS

(a) Joints on S.L. Cable

This type of cable, in which three single-core lead-covered cables are laid up together and armoured over the assembly, is convenient for short runs since it avoids trifurcating joints for single-core terminations, but is difficult to justify for long runs. It is usually only used for 33 kV, and very occasionally for 22 kV. A joint on a single lead cable consists of three normal single-core joints placed side by side or in triangular formation. The latter is the more compact form, and is shown in Fig. 6. The middle joint, which is at the bottom, has extensions to the filling nozzles, so that all three joints can be completed before filling. Tie rods are shown, for inclusion when required. As an alternative to wire armour, a stranded steel wire may be built into each filler space and attached to the tie rods.

(b) Barrier Joints

These are used as a safety measure on gradients, though the evidence for their necessity is conspicuous by its absence. The cable compounds commonly used will flow on a sufficient gradient, though very slowly, and it is usual to insert barriers at suitable vertical intervals to limit the static pressure. The author has no figures for the static pressures reached in practice, and any such data which may be available would be of interest. It is probable that the theoretical static pressure is rarely, if ever, reached with the cable cold. If it were, switching-on full load would cause an expansion of compound which could not be relieved longitudinally before sheath distension occurred. Slight distension may happen occasionally, without shortening the life of the cable. If complete settlement of the compound does not take place while the cable is cold, and substantial pressures only occur when warm, the greater fluidity of the compound will then probably permit longitudinal flow to relieve the pressure, and partially or wholly compensate for any downward flow during cooler periods.

Barrier joints are usually placed at intervals, to limit the theoretical static pressure to that corresponding to a stress in the cable sheath of about 160 lb. per sq. in. This is well in excess of the yield point of lead, and it can only be said that the method has been found satisfactory, probably for the reasons given above.

Two types of barrier construction commonly used are as follows:—

(i) A porcelain similar in form to a bushing insulator, mounted on a plate bolted between the two portions into which the joint sleeve is divided. It has ground facings at each end, and is jointed in an oiltight man-

ner to the barrier plate by an external flange at one end, and at the other by an internal flange to the cable connector. The attachment is made by copper braids, to provide a flexible connection and thus avoid stressing the porcelain. This construction is shown in Figs. 8 and 9. The method shown of attaching the insulator to the plate by springs compressed behind the flange gives constant uniform pressure on the gasket, and ensures a permanently tight joint. The construction results in the two portions of the sleeve being of unequal length, the longer end containing the insulators, and this end is placed on the downhill side so that its larger capacity serves as a compound reservoir. The other end will receive any pressure, and the insulators are mounted so that the pressure pushes them against their seatings. Fig. 8 shows tie-rod construction; experience indicates that tie rods are desirable where they are made possible by wire armouring, as there may be some tendency for creepage on a slope on which barrier joints are used, and the flexible conductor joint would, without tie rods, allow any stress to come on the cable sheath.

(ii) A tight-fitting cylinder of insulation encasing the conductor and passing through a clamping device gripping its middle portion in an oiltight manner. The clamping device consists of a lead sleeve surrounded by a cone grip which compresses it upon the insulating cylinder.*

The simplest principle of barrier construction is the application of an impervious layer, such as oiled-silk tape, over the conductor joint, and extending along the core insulation and on to the sheath at each end. This layer can be reinforced by further wrappings which need not be impervious. The author is not aware that this construction has been used, and it has the disadvantage that the cable is cut off from the compound in the joint sleeve. A lead sleeve could be used for a joint of this type, but, for the two normal constructions referred to above, a rigid sleeve—usually of copper or iron—is necessary to provide a mounting for the barrier plate.

(c) Tee Joints

These are usually limited to a voltage of 22 kV for 3-core and 33 kV for single-core cable. The sleeve may be made of cast or pressed sheet lead in two halves joined on a horizontal plane, the upper half fitting into a groove in the lower; or of lead sheet dressed to the required form, the sleeve being constructed in one piece with the top and bottom portions joined along the top of the T. Fig. 10 shows a 22-kV joint of the former construction. The sleeve has an internal cast-iron support in two halves.

For the higher voltages it may be difficult to force apart the cores of the main cable to allow sufficient freedom for jointing. In extreme cases it may be necessary to cut the cores and slightly separate the ends. A braid connection is convenient in such cases. Jointing would be further eased by changing the connections one-third of a rotation to straighten the run of the cores, but this is of course rarely permissible.

* British Patents Nos. 340426 and 358796 of 1931.

(d) Expansion Joints

In ground subject to subsidence, the possibility of joint failure through pulling-out of the cable may be much reduced by expansion joints, wire armour on the cable, and tie rods. If subsidence occurs such as to damage an ordinary joint, it is found that the conductor joints pull out first, and further movement may take place before the cable sheath is stretched to fracture point.

Expansion joints allow movement of the conductors by connecting them with copper braids provided with a few inches of slack.* The use of these will defer, and in some cases avoid, breakdown. A 22-kV 3-core expansion joint is shown in Fig. 11. It is usual to tin the surface of the cable sheath, using a blowlamp and sticks of solder, for a length of 4 in. adjacent to each wipe. The slight strengthening effect tends to distribute the stretch and prevent fracture at the wipe where the lead has been weakened. Subsidence will cause compression if it takes place at a peak position or at the top of a slope, i.e. where the cable profile is convex upwards. This may be followed by tension resulting from adjacent settling. The alternation of stress in a joint at such a position may cause damage to the cable insulation at the fork, and it is found that expansion joints under severe conditions sometimes fail here. Wood protection boxes are usual for expansion joints, as they have an ample life. These joints have also been used to eliminate stress in the conductor joints due to large section or heavy loading, but the author is not aware of any evidence for the necessity of this. Designs have been produced for providing for sheath movement by means of a metal bellows between the wipe and the sleeve, or by a telescopic gland, but it is usual to rely on the ability of the sheath to stretch.

(4) TERMINATIONS

The problem differs from that of jointing in regard to both the electrical and the mechanical requirements. It is, in general terms, to make external electrical connection to a high-voltage conductor in a hermetically sealed enclosure. A special form of bushing insulator connected as compactly as possible to a wiping gland is therefore used. Where cables are terminated in switch-

Table 1

Working voltage	Dry test, 1 min.	Wet test, 30 sec. (outdoor type)	Minimum dry flashover
kV	kV	kV	kV
0·66	3·5	3·5	4·4
3·3	16	16	20
6·6	22	22	28
11	30	30	38
22	55	55	70
33	80	80	100
44	106	101	135
55	132	125	165
66	170	160	210

* British Patent No. 12146—1909.

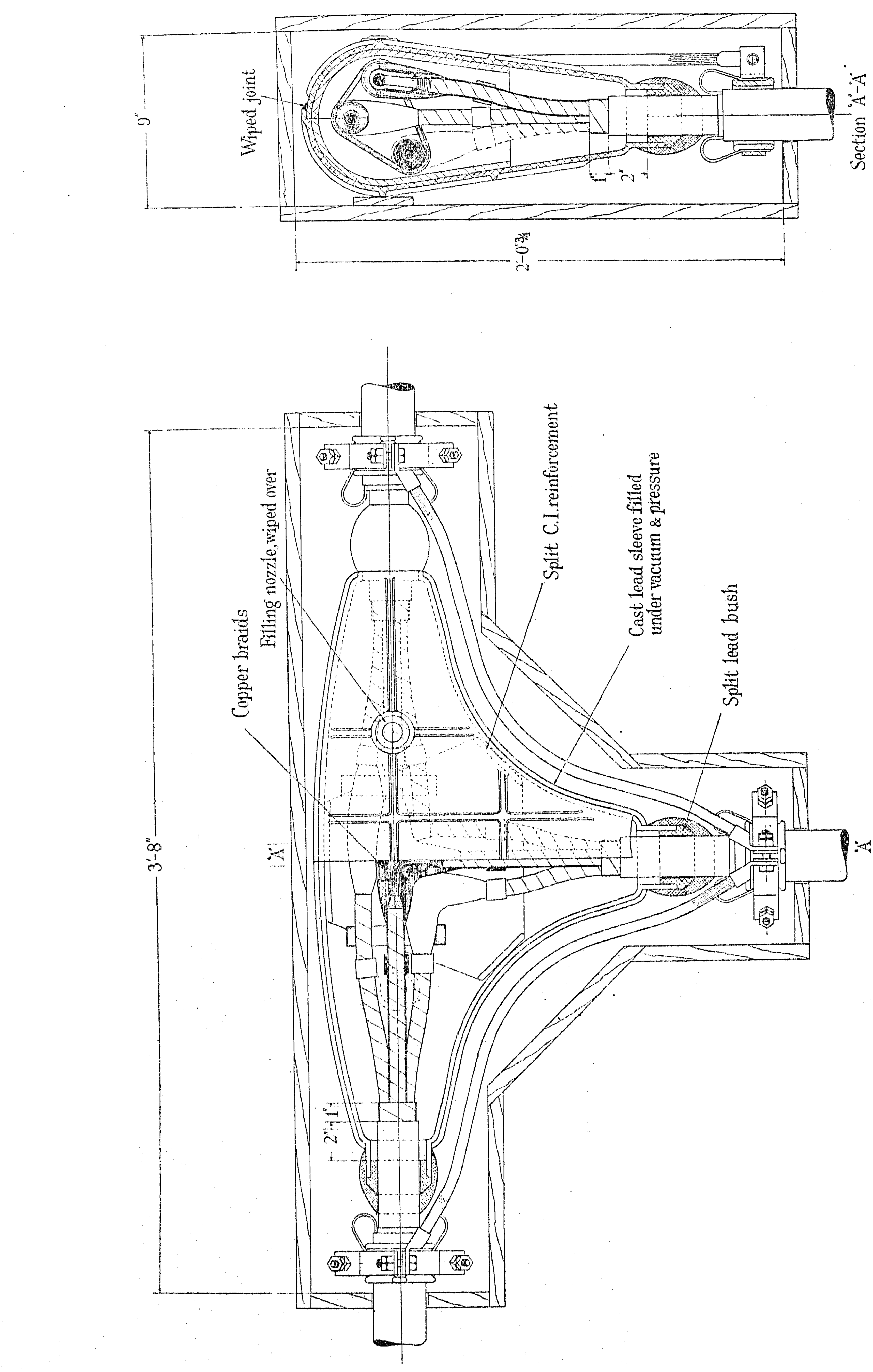

Fig. 10.—22-kV 3-core tee joint.

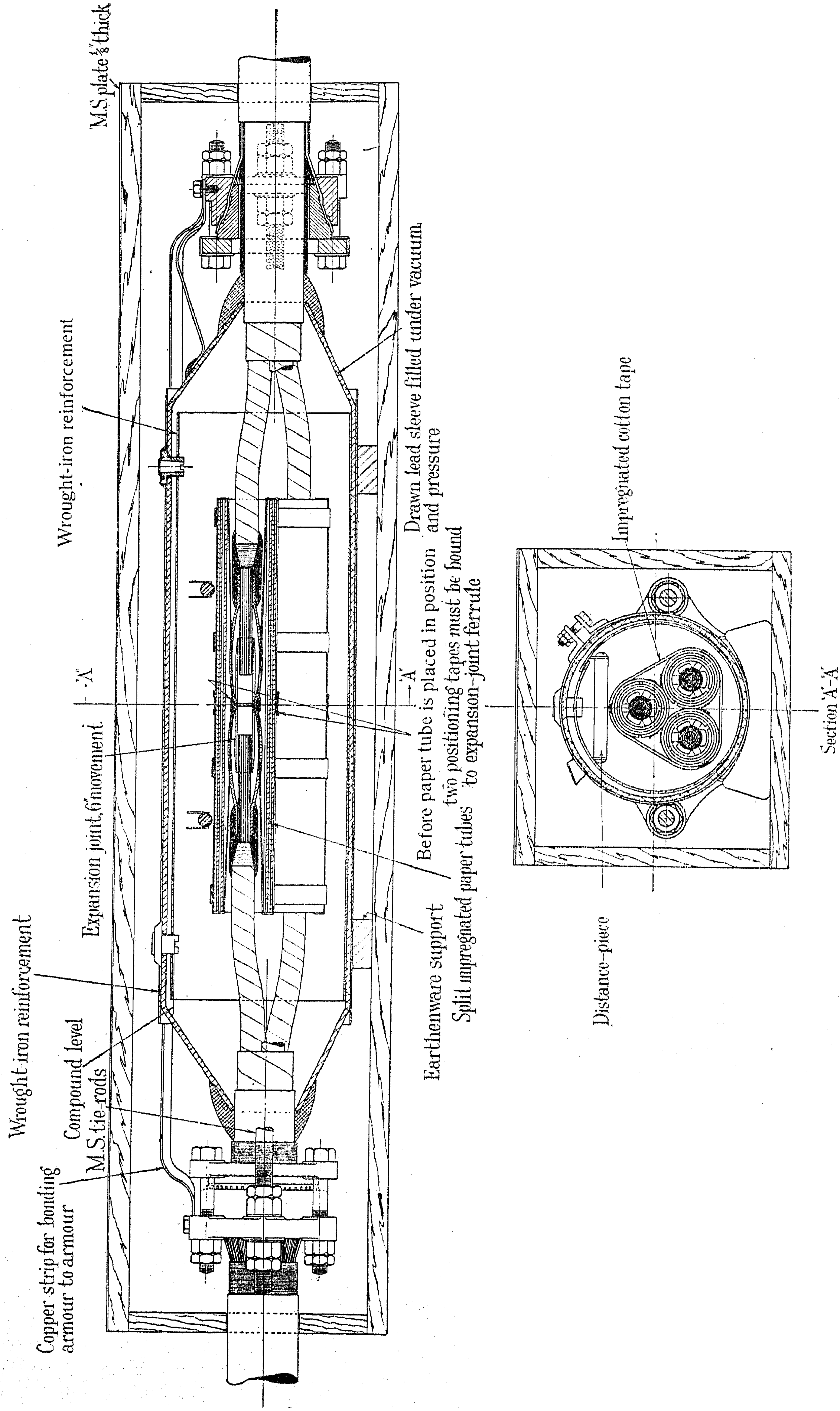

Fig. 11.—22-kV 3-core expansion joint.

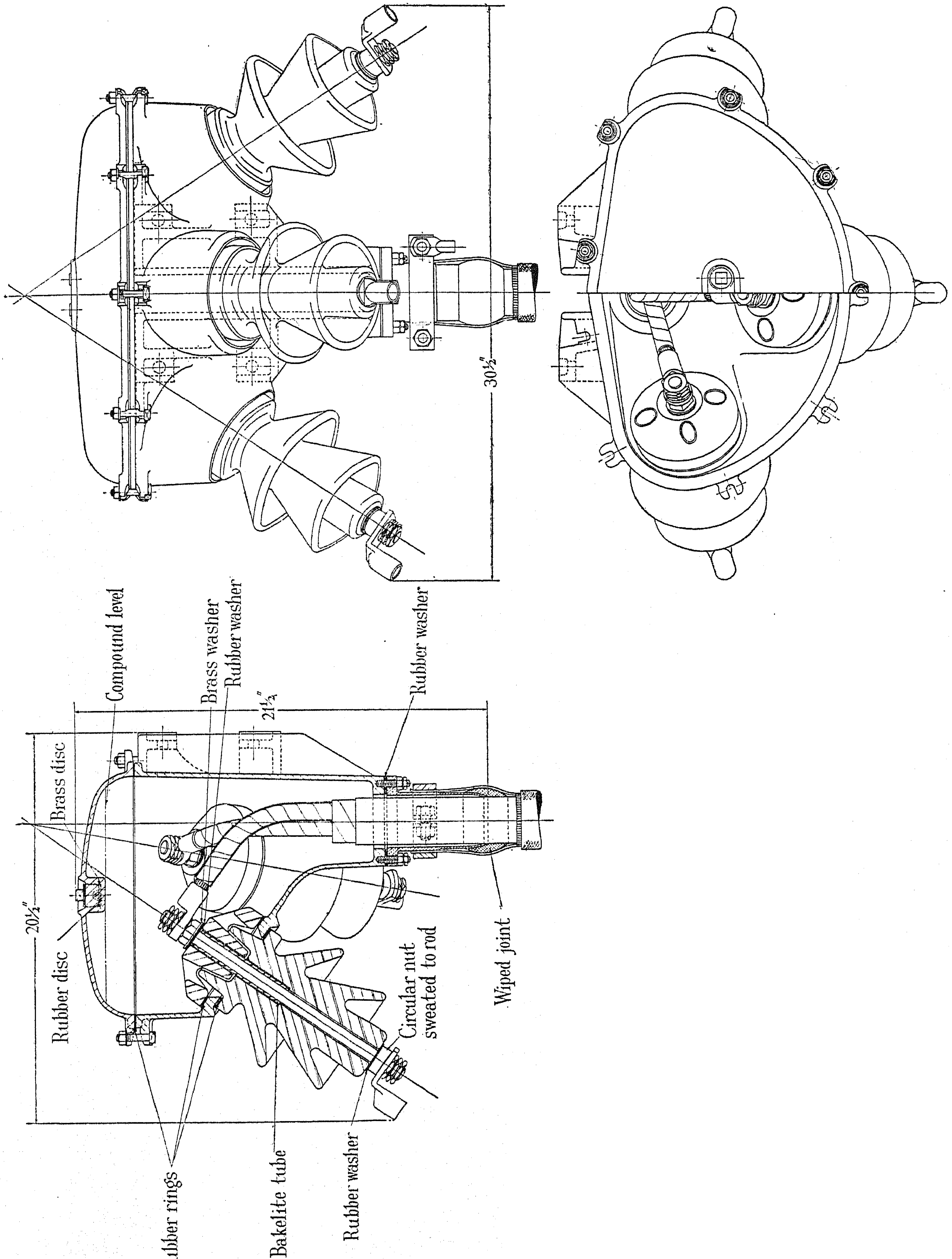

Fig. 12.—22-kV outdoor terminal box.

gear or transformer chambers, there being no immediate external connection, the principle of construction resembles that of a joint. The type of termination here considered is the self-contained unit with an outside connection, commonly known as a "sealing-end" for single-core cables, and as a "terminal box" for 3-core. The term "dividing box" is to be deprecated, as it is equally applicable to a trifurcating joint.

B.S.S. No. 223—1931, for the "Electrical Performance of High-Voltage Bushing Insulators," gives test voltages for each working voltage, and so determines the size of insulator. The test values given in this Specification for normal atmospheric conditions are quoted in Table 1.

It is not apparent why a distinction between the dry and the wet test is introduced only above a working voltage of 33 kV.

(a) Methods of Construction

The form of the ends of the insulator to receive the metal parts depends upon the efficiency of sealing required, and the method of insulator attachment is the principal feature of construction.

For terminals to contain hard-setting compound, the cost of a design which is completely airtight before filling is not warranted, and joints in boxes are therefore arranged to be below compound level. It is therefore essential that a suitable compound should be used, i.e. one which is not liable to crack. Cracking may occur with brittle compounds at low temperatures, resulting in breakdown due to penetration of moisture.

Alternative methods of attachment of insulators are as follows: (i) By using a grooved insulator clamped between the two halves of a box split on the centre line. (ii) By a collar on the insulator held to the box by a clamping ring and gasket. (iii) By a central rod passing through a two-piece insulator, one piece being outside the box and the other inside, the two being pulled together by the rod, with the box wall and gaskets between (see Fig. 12). It will be noted that access to the inside of the insulator for the filling compound is provided. (iv) By cementing into the box lid, or by a metal ring screwed in or attached by studs and nuts.

These methods are applicable as shown in Table 2.

Method (iii) has the advantage that the outer part can be replaced alone in case of damage. Method (iv) is illustrated in Figs. 14 and 15. In the latter, the metal faces surrounding the insulator meet, limiting the compression of the gasket. The gasket is thus uniformly compressed, and not to the point of destroying the resilience of the material. A gasket made of highly compressible material, such as cork or oil-resisting rubber, must be used. In addition, in Fig. 15 a fluid seal* is provided in the annular cavity shown. The gasket extends across the sealing space, being perforated in this part to allow access of the fluid to both sides, and makes

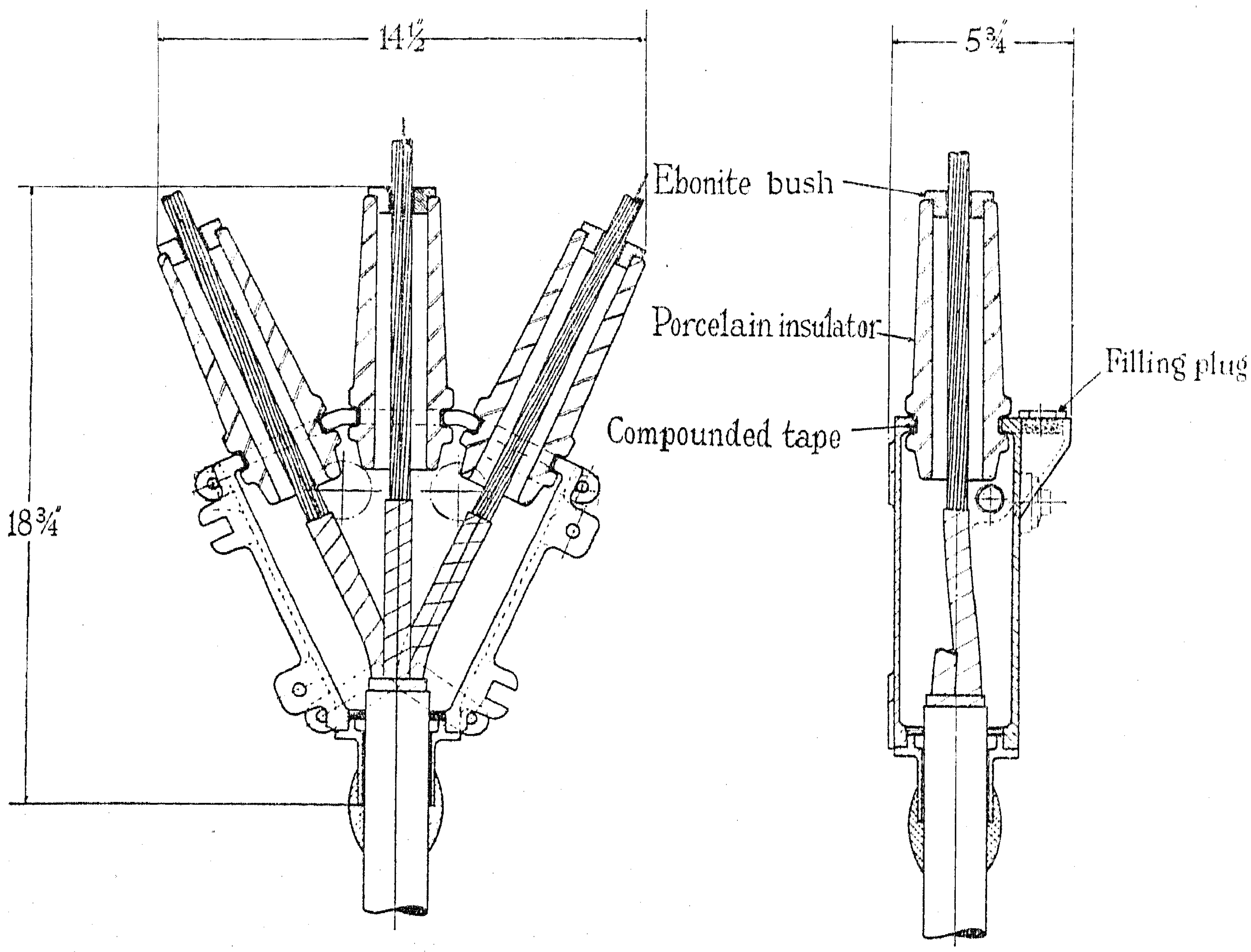

Fig. 13.—11-kV indoor terminal box.

Table 2

		Terminal boxes	Sealing-ends
Hard compound	Indoor	(i)	(ii), (iv)
	Outdoor	(ii), (iii), (iv)	(ii), (iv)
Fluid compound	Indoor	(ii), (iii), (iv)	(ii), (iv)
	Outdoor	(ii), (iii), (iv)	(ii), (iv)

* British Patent No. 367777—1930.

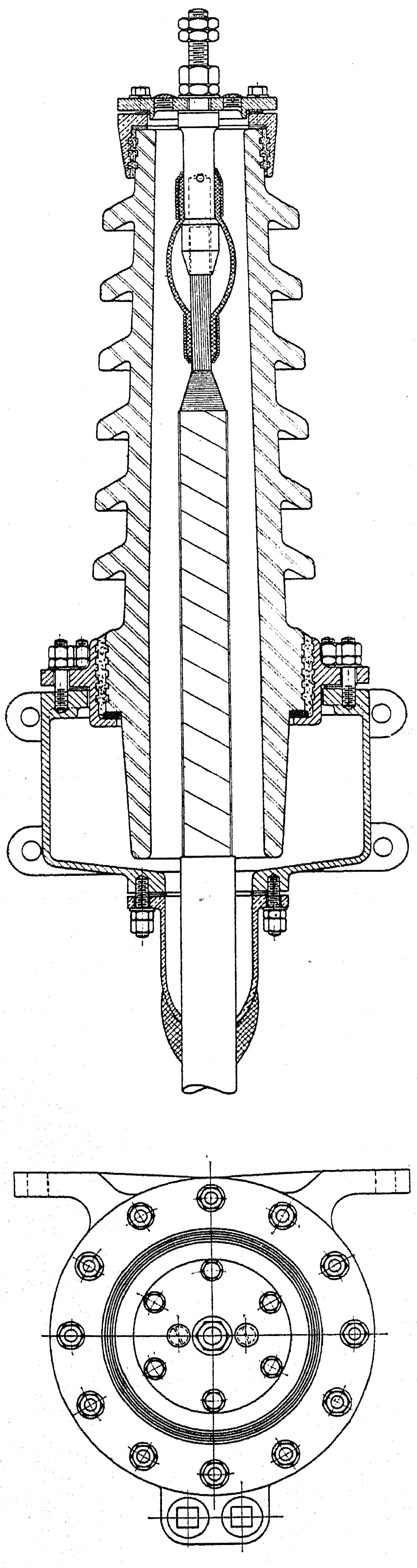

Fig. 14.—33-kV outdoor sealing-end insulator.

a tight joint between the inner portions of the surrounding metal faces.

The construction at the line-connector end of the insulator follows to some extent from that at the fixing end. There are three types of construction: (i) Cable strand or plain rod brought through an upright insulator, which is solid compound-filled; the end is closed by a bush of insulating material (see Fig. 13). (ii) A rod through the insulator, with washers and nuts on each end to retain the compound filling. For fluid compound the external nut should be soldered to the rod. The space between the rod and the insulator is compound-filled, and this may be done in the factory with hard compound, or passages may be provided for filling after erection (see Fig. 12). (iii) A cemented-on cap or ring with cap attached. The connector rod may then go through the cap, or the cable core may have a flexible internal connection, the line connection being taken from an external clamp or stud, thus eliminating the hole required for the rod (see Fig. 15). This has only one gasket joint, the flexible connection being extended out of the dome, which is elevated while attachment is being made to the cable socket.

A construction sometimes used is a small metal bellows plumbed to the cap and conductor, thus permitting slight conductor movement. This arrangement may be criticized on the score of robustness.

Fig. 14 is given for its historic interest. It shows one of the earliest designs of 33-kV sealing-ends, many hundreds of which have been installed. No failure at 33 kV has been reported, though a number of cases have been found where moisture had entered, possibly through the connector rod being disturbed when line connections were being made. The box at the base of the insulator proved to be an unsatisfactory method of providing against migration of compound, as after a time the level fell in the insulator, and so vertical fluid-compound-filled insulators now usually have a reservoir at the top. A considerable number of sealing-ends of this type have been modified by the addition of such a reservoir, at the same time an internal flexible connection being made and the connector-rod hole being eliminated.

The cementing method of insulator attachment is used for sealing-ends, for the following reasons. For a terminal box the box is necessary to provide for the separation of the cable cores, and gives adequate clearance for the connections at the inner ends of the insulators. Any need for a box is avoided in the case of a sealing-end by allowing the cable core to extend up into the insulator. A central rod thus not being available to pull up the sealing joint at the top of the insulator, cementing is resorted to. It is then convenient to use the same method at the other end.

The insulators of terminal boxes are usually inverted, i.e. they point downwards from the box. The advantages of this over upright fixing are: (i) The lid provides access to the interior without removing the insulators. (ii) It facilitates the filling of the insulators with compound (unless they are factory-filled with hard compound). (iii) It enables all live parts and connections to be below the compound level in the box. (iv) Overhead-line connections can be approximately in line with the insulators, thus reducing the stress upon them.

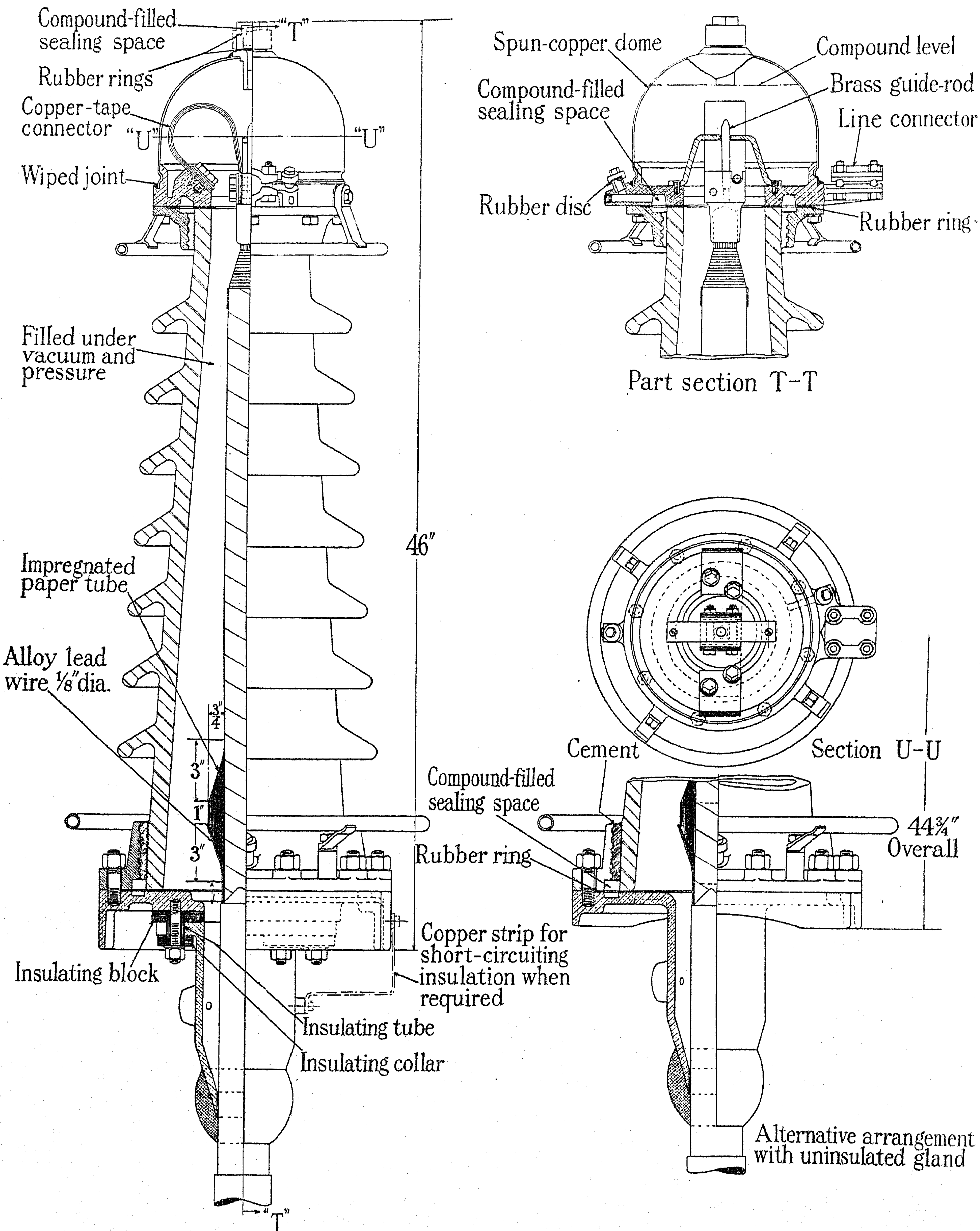

Fig. 15.—66-kV outdoor sealing-end insulator.

While sealing-ends with inverted insulators would in many cases offer the same advantages, the increase of cost due to the box and fittings would not be warranted. This would be greater than the saving due to eliminating a reservoir at the top of the insulator, where used. Moreover, sealing-ends are frequently installed in situations where vertically-fixed insulators are most suitable.

(b) Points of Design

The following are the principal requirements, apart from the provision of a suitable insulator and adequate external clearances. They apply mainly to fluid compound filling.

(i) Airtightness.

The wide temperature range normally occurring results in periods of vacuum which accentuate this necessity. Airtightness will ensure watertightness and compound-tightness. It is more difficult to secure than in the case of joints because of the incorporation of an insulator, the bringing-out of the electrical connection, and the impossibility of sealing the assembly by immersing in bitumen. The construction at the ends of the insulator is chiefly concerned, and has been dealt with. A good design of filling orifice is shown at the top of Fig. 12, its main feature being an enclosed jointing washer protected from friction by the metal disc above it.

(ii) Internal clearances.

Table 3 gives safe working values for application in cable terminations of all kinds for earthed systems. The form of the metal parts between which flashover might occur has a bearing on the distance required. These figures are intended only as a safe guide, assuming that sharp corners or edges do not occur at positions of maximum stress. In sealing-ends, where the cable core is, as is usual, continued up into the insulator, the resulting length, due to the necessary length of the insulator, is more than sufficient.

(iii) Filling compound.

What has been said in Section (2)(*e*) also applies here.

(iv) Drainage of compound.

The considerations for joints apply also to terminations. At the voltages for which a fluid compound is required it is undesirable to prevent the free access of the compound to the cable end.

For sealing-ends the compound reservoir required is best accommodated on the top of the insulator, as shown by Fig. 15, and in the box for terminal boxes with inverted insulators. The increased tendency to drain, due to the usual vertical run of cable, may, for outdoor terminations, be partly or wholly compensated for by sun heating. This should not be relied on, and a surplus compound capacity equal to 1/45 of the paper and compound volume in half the adjacent cable-length is a fair allowance.

With fluid filling it is advisable to examine the compound level, say a year after installation, and subsequently according to the level last found. If the termination is placed lower than the cable the compound level should be set initially at the lower limit instead of the upper.

(v) Expansion of compound.

A suitable allowance for expansion is 5 per cent of the volume of compound in the terminal, plus 1/200 of the paper and compound volume in half the adjacent cable-length. This is larger than for joints on account of the weaker construction and larger temperature-range.

Table 3

CLEARANCES (IN INCHES) UNDER COMPOUND

Phase voltage, kV	3·3	6·6	11	22	33	66
Phase to earth through compound	$\frac{3}{4}$	1	$1\frac{1}{4}$	2	$2\frac{3}{4}$	$6\frac{1}{4}$
Between phases through compound	$\frac{7}{8}$	$1\frac{1}{4}$	$1\frac{3}{4}$	3	$4\frac{3}{8}$	$10\frac{1}{2}$
Along immersed surface between phases. Conductor to sheath along cable insulation	$1\frac{1}{4}$	2	3	$6\frac{1}{4}$	10	24
Along other immersed surfaces to earth	1	$1\frac{1}{2}$	$2\frac{1}{4}$	4	$5\frac{7}{8}$	$14\frac{1}{4}$

(vi) Expansion of conductor.

In 3-core cables, conductor expansion is accommodated in the spiralling of the cores. With single-core cables of large section severe end-thrust may occur if the conductor is rigidly held. A very small movement will relieve any stress, and is covered by the flexible internal connection frequently provided for assembly purposes (see Fig. 15).

(vii) Stress control.

The stress conditions are more severe than in a joint, through the absence of an enclosing equipotential surface, and as the solution of a continuous screen is not available a larger stress cone is usual practice. Fig. 15 shows paper-tube and lead-wire construction, and Fig. 16 shows five designs of 66-kV stress cone. Designs (*a*), (*b*), (*c*), and (*d*), have been employed in practice, and illustrate the divergency of design existing. Design (*e*) is an experimental one, referred to later. Some form of condenser construction is sometimes used, but experience does not indicate that this is called for, nor does it appear certain that it is advantageous up to the voltage limits in question.

(c) Bonding and Earthing

Three-core terminal boxes are usually earthed by being

mounted on an earthed support, or connected to an earth plate. For sealing-ends, the situation is affected by the possibility of circulating currents in the cable sheaths. Feeders consisting of three single-core cables should have the sheaths bonded and earthed at each end of a run at the point where they separate, and insulated at the terminations. Earthing the sheaths at the terminations would result in increased sheath currents which, for short lengths of large-section cable, would cause serious heating. Copper strip of, say, 1 in. × $\frac{1}{8}$ in. section encircling the three cables, and patch-wiped to each, makes a convenient bond, the cable coverings being made good by a wood or iron box filled with bitumen.

making use of machines for applying tape and paper tubes seem unlikely to find more than a restricted use.

Tests made with moulded material have, however, proved promising. A mould is fitted around that part of the cable which it is desired to insulate. The powder is placed in a force pump and made plastic in a hot oil bath. The pump is then connected to the mould, and the contents injected until extrusion takes place from small holes in the least accessible parts. The mould is removed after cooling, and the body of insulating material, which is translucent, can be inspected to verify its homogeneity. Fig. 16 (*e*) shows a 66-kV stress cone formed in this way. In joints, the material is moulded

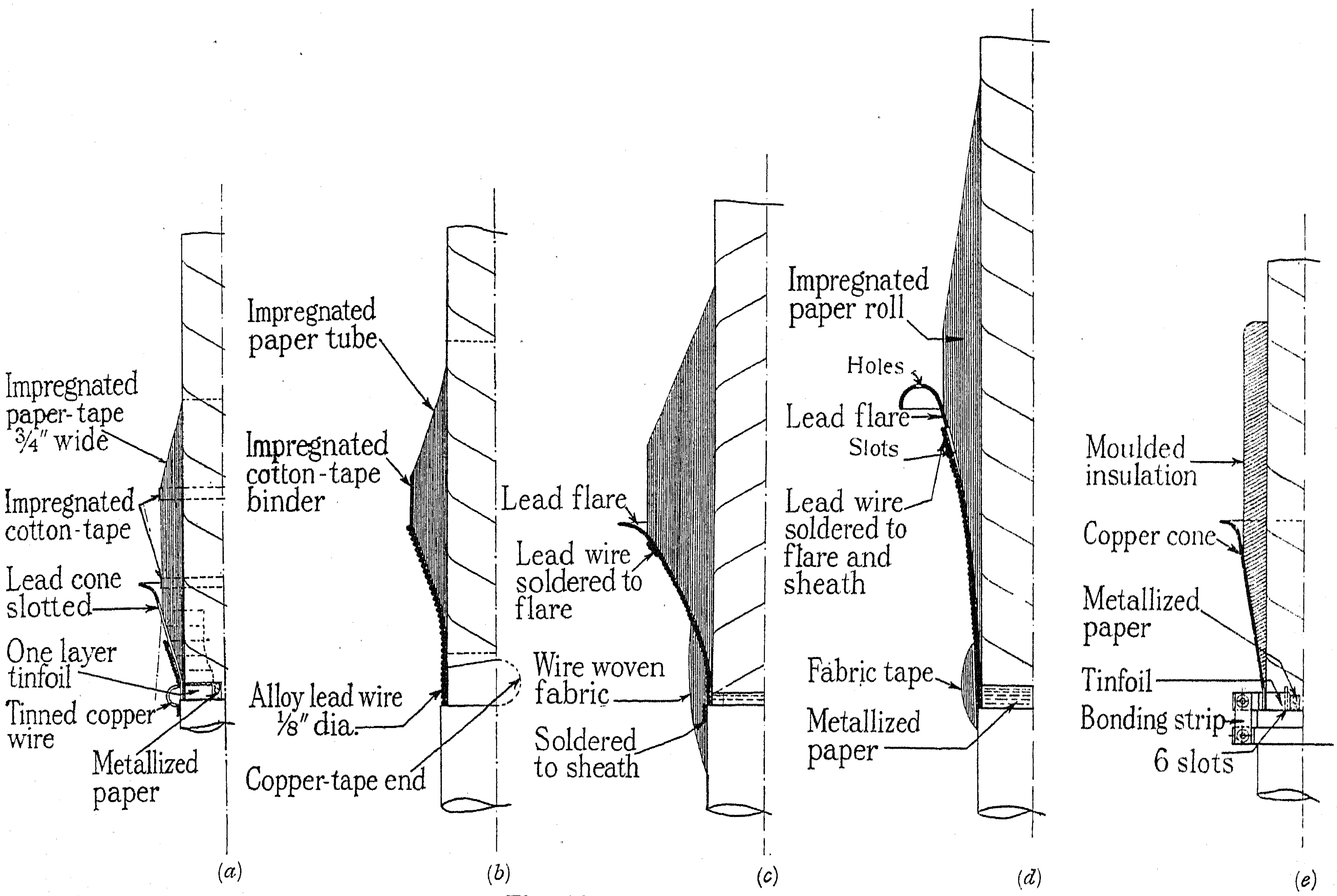

Fig. 16.—66-kV stress cones.

The insulation of the sheaths at the terminations may be effected either by insulated glands (see Fig. 15) or by mounting the sealing-ends on wood blocks. In the first case a flashover would go to earth by the supporting structure, and in the second by the cable sheath; the latter would appear preferable. With wood-block insulation a longer creepage distance can be obtained, 2 in. being usual as compared with $\frac{1}{2}$ in. or so for insulated glands.

(5) FUTURE DEVELOPMENTS

A development which may have an important influence in the future is the use of some of the recently developed synthetic moulding powders for the primary insulation of joints, and the buffers of stress cones. Attempts to mechanize the process of insulating by

directly on to the jointed conductors and adjacent cable dielectric. The sleeve is then filled with fluid compound in the usual manner.

(6) RELIABILITY TESTING

In the testing of a new design of joint or terminal, allowance must be made for variations in construction and for variations caused by operation. As with cables, no rapid method has been found of proving the reliability of a joint or terminal design for the higher voltages. Conditions arise in service which cannot be reproduced in a short-time test, and the successful application of several times working voltage for some minutes, or a less increased voltage for some hours, does not give certainty of unlimited life.

Some hold the opinion that heat cycles must be com-

bined with voltage tests to obtain reliable results. This may be correct for designs where the filling compound has not free access to the insulation, so that heating and cooling in service may deprive the inner layers of compound. Where free access is permitted and a fairly fluid compound used, however, improvement of impregnation during heat cycles is likely, and it seems probable that a voltage test alone is at least equally severe.

An inherent adverse factor arising in service is the state of partial vacuum liable to occur in a joint or termination. This lowers the electric strength, but a satisfactory allowance for this cannot be made in testing as the duration and degree of vacuum are unknown. Tests should therefore be made at atmospheric pressure by leaving a filling orifice open, to keep results on a comparative basis.

More informative results will be obtained from tests on a few units with controlled defects in construction greater than may be expected in practice, than from a larger number made in an average manner. A usual specification test is 4 times working voltage for 15 minutes. This is severe enough for a short-time test, and, given sound principles of design, is a fair indication of reliability.

The author does not presume to propound a standard test which will prove a design and be at the same time as brief as possible.

(7) MOISTURE: EFFECTS AND TESTING

The effect of moisture in suspension or solution on the electrical properties of insulating oils is complex. A curve has been given by F. W. Peek* for the reduction of breakdown strength of oil due to moisture; this curve commences at 70 kV for dry oil and shows 30 kV for oil containing 0·2 part moisture in 10 000, 16 kV for 2 parts in 10 000, and flattens out to 10 kV for 10 parts in 10 000. This curve is for a disc gap of unspecified dimensions.

A technical report (Ref. E/T 37) issued by the Electrical Research Association gives the effect of the admixture of fibre and moisture, (*a*) alone and (*b*) together. According to this report, the effect of the presence of moisture or fibre alone on an insulating oil having an initial strength of 100 kV on a 0·15-in. gap with $\frac{1}{2}$-in. spheres is given by a curve which becomes nearly asymptotic at 75 to 80 kV, with admixtures of the order of 1 cm.^{3} of water, 30 mg. of cotton fibre, or 200 mg. of pressboard fibre, in 10 000 cm.^{3} The effect of greater amounts is not given. Much smaller quantities of moisture and fibre together—for example, 2 mg. of cotton fibre and 1 cm.^{3} of water in 10 000 cm.^{3}—will reduce the strength to between 10 and 15 kV.

A suitable specification test for insulating oil is 30 kV (r.m.s.) on a 2-mm. gap between 13-mm. spheres, but if the oil is perfectly clean and dry a value of about 60 kV is obtained.

The usual method of testing the dryness of compounds used for filling joints and terminal boxes on solid-type cables, and of insulating materials supplied in compound, is by some form of crackle test. This depends upon the fact that oil or compound containing moisture in any harmful quantity will, when heated above the boiling point of water, emit a crackling sound. There are four methods of carrying out this test: (i) By allowing drops of the compound to fall into a vessel of similar or other oil or compound at a temperature of about 130° C. (ii) By heating a sample to 130° C. (iii) By immersing in a sample a small metal object at red or white heat. (The end of a piece of the cable conductor wire formed to a short spiral by wrapping on a pencil and heated by a blowlamp is convenient.) (iv) By heating the whole of the compound to be tested to 110° C.

A lower temperature is chosen for (iv) than for (i) and (ii) in order to avoid damaging the compound. For (i), (ii), and (iii), the compound should be well stirred to ensure a representative sample. Method (iv) may be regarded as the most certain, but is laborious where large quantities are involved. Method (iii), the "hot wire" test, is the most convenient and, with care to obtain average samples, may be safely used.

A simple investigation of the sensitivity of the hot-wire test was made some years ago by the author. It was found that by introducing 0·005 per cent of water into a crackle-free oil-resin compound a distinct reaction was produced. Repeat tests and precautions to get thorough mixing were taken. The result indicated that the addition of more than 0·001 per cent or 1 part in 100 000 of moisture should be just detectable. It may be noted, however, that the exact degree of dryness before adding the water was unknown, the only information being that it was crackle-free.

While experience indicates that it is a simple matter to verify by tests that oils and compounds do not contain a harmful amount of moisture, there is a lack of complete information. The matter is of some academic interest, and a systematic investigation of the effects of moisture in different states and amounts on the crackle test and on the electrical breakdown test when applied to various oils and compounds, both clean and containing specified amounts of fibre, might lead to results of practical value.*

The testing of insulating tapes for moisture is carried out by dipping in oil or compound at about 130° C. Paper tape is dipped for about 2 sec., and moisture shows as froth on the surface on withdrawal. Cotton tape requires dipping for a rather longer period.

In the section on filling compound [Section (2) (*e*)] reference has been made to the application of pressure through the medium of atmospheric air. As a check on the moisture which might be introduced in this way, a lead sleeve 9 in. long × 4 in. diameter was half filled with oil-resin compound. This was placed outside in damp weather, sometimes raining, and pumped up to 30 lb. per sq. in. with atmospheric air. During a period of 2 days the pressure was released and immediately restored 10 times. The sleeve was then warmed and the compound shaken up, to mix any deposited moisture. Hot-wire tests were carried out before and after this treatment, and the two gave —as nearly as could be judged—equal results, indicative, on the basis of the test described above, of about

* "Dielectric Phenomena in High Voltage Engineering" (McGraw-Hill, 1929).

* Some preliminary information in this direction is given in E.R.A. Report Ref. E/T46.

0·001 per cent of moisture. Apparently this amount gained access during the charging of the sleeve, and was not appreciably increased by the air-pressure process.

(8) BREAKDOWNS: CAUSES AND EXAMINATION

While there are similarities in the electrical operation of a joint and the cable to which it is connected, and in regard to the conditions of the insulation which may lead to failure, there are considerable differences in the predisposing causes, owing to the dissimilar construction and dimensions. Some analysis of these will now be given, but no attempt will be made to analyse the mechanism of the breakdown of materials, which is fully and more appropriately dealt with in the literature of cable technique.

The determination of the cause of failure of a joint or terminal is frequently difficult through the destruction of evidence by the breakdown, and the subsequent penetration of moisture, though this is true to a less extent than with cable failures. Assuming a sound cable, the causes of a joint or terminal failure, which are rarely due to mechanical damage, but rather to defective design, materials, or construction on site, are as follows:—

Design.—Cramped dimensions, defective protection from moisture, improper stress distribution.

Materials.—Inferior insulating materials (including compound), defective sleeve parts (admitting moisture).

Construction.—Sharp projections on or near live parts, use of damp insulating materials, badly applied taping (occluding air), defective plumbing or other cause of admitting moisture.

Operation.—Subsidence (causing breakage of conductor joint or adjacent cable-sheath), drainage of compound into cable, collapse of lead sleeve (due to drainage and vacuum), development of partial vacuum (causing reduced electric strength).

Some general principles of the examination of failures are mentioned below.

When a joint sleeve is found broken, wetness of the outer layers of insulation combined with dryness of the inner implies entrance of moisture since breakdown. A less degree of contrast between the outer and inner layers will indicate that the moisture was present before failure. In this case evenness of distribution combined with examination for any point of entry may again provide some clue as to whether the moisture has been left in initially or has entered during service. The jointing record should also be referred to. Breakdown between cores at the fork is probably due to rough handling during jointing, except in the case of expansion joints.

A procedure of examination may be outlined, as follows.

First, observe the site conditions in regard to moisture and possibility of subsidence.

Before disturbing the joint, collect any evidence as to compound level before breakdown. If the sleeve is broken, observe the quantity of compound about, the state of the insulation, and look for a "high water mark" in the sleeve.

At the first opportunity trace the breakdown path. This may not be found until the joint is dissected, and in some cases—especially if the path is through compound only—it may be untraceable.

Next, cut off each cable about 1 ft. from each wipe, and remove the joint to a convenient place for examination.

Then drain off the compound, heating the sleeve with blowlamps. In doing this, observe the source of any water.

Now examine the assembly in comparison with the drawing.

In case of moisture, examine the wipes for visible signs of porosity, and also examine the sleeve for possible points of entry of water. The tightness of bolts and plugs should be checked by tightening.

Next, dismantle the cores, examining the workmanship and testing for moisture. If they will not draw out of the cable sheath, cut off the cables adjacent to the wipes. The stress cones (if any) should first be undone, and then the hand-wrapped insulation. Observe the distribution of moisture, correlating it with the breakdown path and the features of the sleeve. Note any parts denuded of compound.

Finally, examine the conductor joints, especially for projections. If there is freedom from moisture, combined with good workmanship and sufficiency of compound, and the breakdown is associated with dry places in the insulation (i.e. not properly impregnated), the implication is that the design is at fault.

A design may, after some years of use, prove inadequate, though with modern methods of testing this is very unlikely. Any resulting failure will probably show dendritic burning without moisture, and examination of the workmanship should reveal whether this or the design is at fault. In the case of a design which can be considered to have been proved by experience, an otherwise inexplicable failure may be regarded as probably due to the development of partial vacuum, a condition which it is practically impossible to guard against, but which only matters at the highest voltages. This condition is distinct from the collapse of a weak sleeve under vacuum, causing failure through reduced clearances and loss of compound.

Acknowledgments

The author wishes to express his thanks to British Insulated Cables, Ltd., for permission to publish the material included in this paper, to his colleagues for helpful criticisms, and to the other firms who have given permission for the reproduction of their designs.

[The discussion on this paper will be found on page 543.]

DISCUSSION BEFORE THE TRANSMISSION SECTION, 9TH DECEMBER, 1936

Mr. S. R. Siviour: A minor criticism of the scope of the paper might be that there is rather an absence of data relating to some of the special designs for 6 kV and 11 kV, particularly in connection with the heavy cables such as for connections to generators, transformers, and switchgear, which introduce severe conditions of operation and installation.

I do not agree that the word "joint" is being overworked. To my mind, it admits of no ambiguity; it covers the whole assembly, and does not refer merely to the conductor. "Joint" is a general term and should be qualified in all cases by an appropriate adjective to indicate the particular use of the joint; I suggest that the use of the word "normal" to indicate a straight joint is not correct. A tee joint or a dividing box is equally a normal joint. Again, the author deprecates the use of the term "dividing box," but to my mind it is much more appropriate than "trifurcating box," which can apply only to 3-core cable, whereas one may have 2-core, 4-core, and 6-core cables. Why not use "dividing box," which applies to the whole range of cables right down to low voltage, and is much more indicative of the use of the box?

On page 517 a record is given of a particular system of 33-kV cable, and in this connection I should like to quote the case of a 33-kV underground system with which I am associated. Commencing with 34 miles in 1926, there were 88 miles in 1927, and there are 108 at the present day; in 11 years there have been only 4 joint failures. Two were in straight joints, and were due to migration of compound; one was in a dividing box, and was due to faulty workmanship; the third occurred in a dividing box in an "H"-type cable after 8 years' use, and was due to migration of compound. Three of the four faults occurred in belted cable, but I agree that the failure of belted cable from the now well-known cause does not necessarily account for the behaviour of the joints in that cable. All the cables in question were laid and jointed by the makers.

I should like to stress a point to which the author has not referred, and that is the importance of the time element in the case of breakdown and the desirability of reducing the time required for jointing—so far as is compatible with the safety of the joint—in order to get the cable into commission again as quickly as possible after a breakdown. I have met with several cases where the cable fault has been localized and the ground opened up within 6 hours, but it has taken another 2 days to get the cable back into commission, the greater part of that time being required for jointing. Any simplification of the jointing problem will therefore be welcomed by supply undertakings.

In Fig. 1 an 11-kV straight joint is shown with a timber box over-all; I have used creosoted timber buried in the ground, but the results vary so much with the type of soil and other local conditions, particularly in industrial areas, that I advocate the use of cast iron or concrete for high-voltage cables in all buried boxes.

The reinforced lead sleeve shown in Figs. 2 and 4 seems to me to introduce unnecessary complications. On 33-kV joints I have experienced no trouble in service with cast-iron sleeves, machine-faced at the joints. I should like the author to tell us what particular advantage he claims for the reinforced lead sleeve.

With regard to paper tubes for the 33-kV and 66-kV cable, one-piece tubes are preferable in that they eliminate the possibility of occluded air.

Turning to the question at the end of Section (2)(*d*), pot wiping is the better procedure, in my view; the mix which I have found generally satisfactory is 35/65.

As regards filling compounds, I agree with the author that it is preferable to use compounds generally similar to that used in the cable, but I see no objection to a higher viscosity in that of the joint to minimize migration to the cable. It is evident from the record of joint failures which I have given that the migration problem has to be faced. In this connection, I am very interested in the reference to Styrene filling. The author says: "It may be questioned, however, whether the cable at the wipe is properly replenished, and whether harmful migration on the lower side of joints on gradients may not occur." Is there any proof that this migration is more than temporary? The cable is at its lowest temperature when the plumb is made, and I should have thought that the temperature-rise in subsequent service would rectify that local deficiency. Although the author does not agree with the practice, I suggest that the provision of oilproof wrappings in the crutch and over the lead sheath of the cable would minimize this local movement of oil.

With regard to the test voltages shown in Table 1, my experience in an industrial area indicates that these voltages are too low. For instance, for a working voltage of 33 kV I should say that 100 kV and 150 kV respectively are minima for the dry- and wet-flashover voltages.

Wiped joints are shown for the terminal boxes illustrated in Figs. 12 and 13. For some years we have used the split lead cone, and this does away with the plumbed joint and greatly facilitates work on the pole top under bad weather conditions.

With regard to sealing-ends, I agree with the author as to the importance of providing for expansion. I can recall some early experiences where large cables with no provision for movement gave sufficient end-thrust to break the insulators.

Mr. T. R. Scott: It is a task of very great magnitude to attempt to include in one record the whole art even of e.h.t. jointing and terminating. Nevertheless, I am disappointed to find that, after promising in his Introduction a discussion of the main principles, the author seems to confine himself rather to a discussion of detailed designs of both joints and terminations. After a very careful study of the paper, I am somewhat at a loss to know what his own attitude is to the main principles of e.h.t. jointing and terminating.

It is an extraordinary fact that no performance figures are given in the paper for any design either of joint or of termination. The only qualification of the designs is that given on page 517, where the author says: "It may be said that joints and terminations can now be made of an electric strength equivalent to that of the cable. If the combination of cable and joints is stressed to failure, the

stressing and the previous history will probably decide which is to be the first to break down." This last sentence, to my mind, raises three questions: First, does the author infer that the cable system is weakened by the inclusion of the joint? His statement is somewhat ambiguous, since the addition of the joint or termination might cause the cable itself to be in a weaker condition. Secondly, what standard of cable performance does he specify? Thirdly, what are the prospects for the future if the cable standard is raised? It is well known that the performance characteristics of the solid-type cable with which the author is concerned have been raised very considerably over the last few years, particularly in the range with which he is dealing (22–66 kV). I think it is highly probable, and I hope it is true, that the performance will be still further raised in future. Some of the author's diagrams represent the practice of 6 or 7 years ago, and it is quite probable that, matched with the cables of those days, his statement regarding the equivalence of joint and cable is correct; but does it apply to the cables of 1936, and will it apply to the cables of future years? If we advance still further in cable performance, what prospects have we of obtaining better joints? I can find no reference to this point in the paper, except under "Future Developments," where the moulded joint is mentioned. If we are to reap the benefit of the cable performance which we hope is going to be achieved in the next few years, we must carry out a considerable amount of research work in order to see that the joints and terminations match up with the cable performance. Much of this work has already been done.

Generally speaking, a cable must be designed either to have longitudinal flow or to prohibit it. From this point of view, I think that in dealing with solid cables one can say with fair security that it would be an excellent idea if all cable lengths had barrier joints of some form at either end, including the terminating length. The trouble so far has been the cumbersome nature and the size of the barrier joint involved. The author apparently foresees no remedy for this trouble.

Joints and terminations must be constructed in the open air, and during that process there is a danger of moisture associating itself with the insulation of the joint. The author deals fully with the oil or compound moisture-absorption, but I do not think that it is so well realized that the moisture which passes into the oil or compound very rapidly penetrates into the cellulose fibres. These, if properly dry, are very good dehydrating agents, and they do their best to rob the compound of moisture. As a result, the fibres may take up moisture and lower their insulation value without the effect being indicated by any of the tests which the author describes, and the completed joint will thus be weakened. Recently a process has been developed whereby the cellulose fibres can be treated so that they retain their ordinary mechanical structure and form, but receive the benefits of practically an artificial-silk moisture-content and insulation-value; in fact, the insulation value is considerably higher than that of artificial silk. The process has already been applied commercially to cotton tapes, and I hope that very shortly it will be available also for paper insulation.*

* See *Electrician*, 1936, vol. 117, p. 658, Fig. 3.

It must be granted—from the author's references to it on pages 517, 525, 529, 530, 532, and 539—that compound migration is a fairly serious business, and Mr. Siviour has already subscribed to this opinion. If compound migration is going to occur, the question is: What type of compound will the cable receive from the joint? From the description in Section (2) (*e*) (iv) it is obvious that there must be a considerable amount of air and at least some moisture which is detectable by the crackling test, and probably also some of the absorbed moisture of the type I have been discussing. The cable is not blessed with the massive insulation of the joint, and if it receives this compound mixed with air and moisture there will be a serious risk of it breaking down quite close to the joint; and it is notorious that quite a number of the faults in cables do occur in regions adjacent to the joint. Either we must improve upon the compound-filled joint described by the author; or the cable, when it receives any compound which has migrated from the joint, must receive compound which has been thoroughly degasified and dried, and which has not again been in contact with air and moisture.

Finally, I suggest that the author stresses a little too much the question of low cost. He refers on page 517 to "unnecessary expense" and on page 518 to economy in cost of materials and economy in installation cost. I would point out that where a joint breaks down or where the cable adjacent to a joint breaks down it usually involves the inclusion of a short length of replacement cable and the addition of a second joint. These cost money.

(*Communicated*): The author has asked me to amplify my remarks regarding the main principles of e.h.t. jointing and terminating by defining these principles. For a detailed discussion of these I would refer him to a paper* written by me some years ago. Summarizing this briefly, I suggest that there are fundamentally only two types of joint, namely (1) Two terminations placed end to end and connected to form a joint. (2) Joints in which an attempt is made to replace the insulation removed from the cable in order to make the conductor joint. Each type has intrinsic problems which have to be solved, but sooner or later one or other type will establish itself as the standard e.h.t. joint for the range of voltages dealt with by the author.

With the exception of the Styrene joint and the moulded joint, the author deals almost exclusively with the former of the two types. He has therefore to face up to the fundamental problems of the termination, namely grading of stress (longitudinally and radially) and provision of accommodation for compound expansion. I do not consider that the inclusion of an air pocket, to act as a "cushion," can possibly be regarded as more than a temporary expedient, which, incidentally, seriously hampers the progress of development towards improved cables. Sylphons or pressure reservoirs may be adopted in the case of terminations to avoid the necessity for an air pocket, but there are obvious difficulties in connection with joints unless we postulate that all joints of the future must be made in accessible positions such as manholes.

* "Supertension Joints and Terminations," *Electrical Power Engineer*, 1934, vol. 16, pp. 713, 779.

To my mind the fundamental principles of joint and termination design must in the future be based on (*a*) Elimination of migration of compound into and from the cable at joints and terminations. (*b*) Elimination of air or gas pockets of all descriptions from cable (solid type) systems. (*c*) Application of high-quality joint insulation in such a way that (longitudinal) stress distortion is eliminated.

Given these joint and termination characteristics, solid-type cable systems will become markedly improved in regard to service performance.

Mr. J. K. Webb: On page 517 the hope is expressed that particulars of other constructions, with their advantages, will be given in the discussion, and this must be my excuse for the remarks which I now propose to make.

With regard to the desirability of using barrier joints, for a 3-phase system the author's solution necessitates three of the enormous structures illustrated in Fig. 9, and as the system may be so situated that such structures are not possible it is perhaps natural that, in Section (3)(*b*), he should find the evidence for their necessity "conspicuous by its absence." Notwithstanding this, he appears to follow standard practice in installing barrier joints under specified conditions of gradient and pressure, and there is very good evidence that such joints have saved a great deal of incipient trouble. The problem is not only one of hydraulic pressure on the lead sheath, although in America there is a tendency to call for barriers or plugs to break up even 50-ft. heads into 25-ft. sections when plain lead-covered cable is used. In the case of armoured cable the lead sheaths could withstand the pressure; nevertheless, there is much to be said for preventing the migration of compound downhill, where it will tend to fill up joints and give rise to very high pressures as the cable heats up. There will also be a danger of developing a partial vacuum in the upper joints, a condition against which, according to the author, it is almost impossible to guard. This condition considerably reduces the electrical strength of the joint.

I should now like to say a few words about Styrene joints, a description of which has already been given elsewhere.* These joints are quite a new departure in the technique of jointing, and they are very economical as regards dimensions. Their electric strength is very good indeed, and, what is more, they seem to improve in service. By the method of their construction the taper is very firmly welded to the added insulation. The Styrene when in the monomeric stage—i.e. when it is liquid—is soluble in oil, and it then penetrates into the taper. When polymerized it hardens, and welds the added insulation to the original cable. The added insulation is quite hard, and is a perfect barrier to the flow of oil.

I should like also to mention another interesting idea. In connection with 33-kV cable for connection to transformers, engineers have great trouble with the thin transformer oil leaking into and running down the cable, and also with the cable compound contaminating the transformer oil. To overcome this trouble the oil at the end of the cable is replaced by Styrene, which is then polymerized. To within a short distance of the end the cable is quite flexible, but it then gradually hardens until the end becomes solid throughout. The Styrene is quite insoluble in oil once it is in the polymerized state.

* *Electrical Times*, 1934, vol. 86, p. 45.

The type of stress cone advocated by the author is only a palliative for a very undesirable state of affairs, namely the considerable stress distortion which occurs at a cable end, either in a joint or in a terminal. So long as the cable is underneath the lead sheath the lines of electrostatic stress are radial, but wherever the cable leaves the sheath there is considerable distortion in the region of the latter. A more scientific method of dealing with this problem is to grade the stress, and for this purpose I recommend the condenser cone.* It effects great economies, and makes cable terminations much more certain.

If the relation between the pressure in a joint such as is described by the author and its electrical strength is determined experimentally it is found that there is an alarming decrease in electric strength as the pressure is reduced; and, with both alternating current and direct current, with full vacuum, the breakdown value is about 2 kV, which is not very good for a 33-kV joint. The possibility of vacuum forming in one of these joints is serious, and it is not sufficient to test them only under atmospheric pressure.

Diagrams of cable-ends are very misleading, because on paper it is possible to draw a cable-end quite straight, whereas in practice it never is so, and if one of these rolls is to be put on the cable it has to be straight; if it is not, there will be a gap between the added roll and the cable, and it will depend very much on the personal factor whether the roll is properly adjusted or not. There is a grave risk of leaving a space which is filled with an air film between the added roll and the cable, and on the whole I think it is surprising that the method proves as satisfactory as it does. Cotton tape has been used in the past, but if such a cone is dismantled after a few years' service the cotton tape is found to look moth-eaten, owing to the action of the electric stress.

The voltage gradient at a cable-end is very steep near the lead sheath. With a condenser cone fitted, however, almost a uniform gradient is obtained.

The author, in his brief reference to Styrene joints, questions whether the cable at the wipe is properly replenished and whether harmful migration on the lower side of Styrene joints on gradients may not occur; but if he will refer to British Patent No. 429611 he will find that the point he raises has not been overlooked.

In conclusion, on page 541 the author mentions 30 kV (r.m.s.) on a 2-mm. gap as a suitable specification test for insulating oil. I should like to ask why he does not favour the test given in B.S.S. No. 148, which specifies a 4-mm. gap.

Mr. J. Urmston: With regard to nomenclature, the word "stress" is frequently overworked and when it is used it ought to be qualified as being either mechanical or electrical. The same applies to the word "pressure." If the pressure is electrical, however, it ought to be replaced by the word "voltage," leaving "pressure" for gas pressure and mechanical pressure.

In Section (2) (*b*) the author states that "Insulation applied under jointing conditions, whether by hand or by machine, is inevitably inferior to the factory-applied

* *Electrical Communication*, 1933, vol. 12, No. 2; and 1937, vol. 15, No. 4.

insulation of the cable. The inferiorities consist of slackness, irregularity, the presence of air and minute traces of moisture, and incomplete impregnation." While I have experimental evidence to show that the paper-lapped joint, tested at high voltage with heat cycles, has a lower factor of safety than the paper-sleeve-insulated and oilfilled joint, I cannot agree that the paper-lapped joint is necessarily slacker and less completely impregnated than the cable. In fact, the experimental evidence I have at my disposal shows that the paper-tape-lapped joint can be harder than the cable. The real weakness of the paper-lapped joint is at the ferrule.

Regarding stress cones, a considerable amount of work has been done on this subject, but little has been published on the principles on which stress cones have been designed. It is now possible to design a stress cone so that breakdown shall occur either at the end of the flare or along the outer surface of the core insulation, just between the core insulation and the paper buffer.

I should now like to make a few comments on what Mr. Webb has said. I consider, and experimental evidence confirms, that the testing of a joint at high voltage is of no great value unless heat cycles are applied. It would be interesting to know whether the Styrene joint was tested at high voltage with heat cycles. Experimental evidence on a similar type of joint shows that trouble can occur at the ferrule under certain conditions. With regard to the graded-stress cone, I should like to mention a method of joint making evolved by my colleague Dr. Brazier.* As the cable is manufactured, layers of tinfoil are introduced between the layers of paper at the ends of the lengths. When such lengths have been jointed together the joint sleeve is simply filled with cable oil. Such a joint in a 60 000-volt cable length has been under test for many months at double working voltage with heat cycles, without failure.

I do not think it is realized how much work is being and has been carried on in connection with the design of joints and terminals. At the present moment, for instance, there is a loop of 300 yards of 60 000-volt cable in the ground containing no less than 25 joints, some standard and some experimental, which has been under test for as long as 10 months. We do not now expect to get much idea of the reliability of a joint from short-time tests. The short-time test is exceedingly useful to the research engineer who has to design joints. The joints are tested at the highest voltage with heat cycles in order to expose weaknesses in a minimum of time. I should like to ask the author a question which I think is quite important because it is becoming general to test cable installations with high-voltage direct current, in order to eliminate weaknesses in both joints and cable. The condition where the joint is stronger than the cable is a very satisfactory one from the point of view of the engineer who has to locate weak spots in cables, but may be regarded as promoting undue costs in jointing. I should therefore like to ask the author what his opinion is: Should the cable be electrically stronger than the joint, or vice versa?

Mr. L. M. Jockel: I should like to comment on one or two purely practical points in the paper. Turning first to Section (2) (*d*), I quite agree that watertightness is the outstanding special feature required of sleeves. The paper says very little about the mechanical strength of sleeves, and I should like to ask the author to enlarge on this point. I have had considerable experience with e.h.t. cable sleeves in urban areas, where the cables were largely drawn into ducts. These ducts were in the main streets of cities and were subject to the usual urban vibration, particularly of tramways adjacent to the ducts. We had a considerable number of breakdowns due to mechanical trouble on the sleeves. I have also had experience of the same thing on 11-kV cables in regard to railways. One of the worst faults with which I have ever had to deal was in the North of England where an 11-kV cable passed under the railway sidings of a very important steelworks. Had the steelworks not possessed a private generating plant in addition to the bulk supply, their output would have suffered considerably for a period of 36 hours. The cables had been laid in the early days of the works; thereafter the railway sidings had been extended, and the cables were some 6–8 ft. below the metals.

Turning to Section (4), from a practical point of view my greatest trouble in recent years has been the bleeding of terminations. I should like to ask the author whether this difficulty has now been entirely and successfully overcome by the cable manufacturers; my experience seems to have been particularly unfortunate. The cable manufacturers always tell me that if they give the cable a highly viscous impregnation the insulation may suffer and a breakdown may result, whereas if a very thin viscous impregnation is employed then bleeding results —even if there is not much static head on the cables.

Regarding Section (6), I should like to ask the author to give his views on the question of a.c. versus d.c. high-voltage testing. I believe that if a cable is going to work on 50-cycle supply and be coupled with transformers and alternators it should undergo an e.h.t. test at 50 cycles, of at least double the working voltage, and with intermittent applications. I have known valve-tested cables tested at three times the working voltage which have eventually broken down, and I am told that such failures are due to transformers which are connected to the cable, or to harmonics or variations in the sine wave due to the transformer.

There is another point in regard to testing on which I should like the author's opinion, and that is the possibility of the hydrostatic testing of cable sheaths. I have met a case where cables broke down which were supplying an important grid substation, and the breakdown was due to having a static head averaging 5 ft. of water on the joints for about 24 hours. They were single-core cables, and they had stood up to all ordinary electrical tests most satisfactorily, but they failed after 24 hours' immersion of the joints due to the flooding of the land adjacent to the substation.

Dr. P. Dunsheath: I should like to ask the author what course he would take if he had a 33-kV screened cable carried on supports so that in the summer the cable was subjected to very high temperatures, and he had a suspicion that the compound was passing from the joints into the cable. Would he open those joints and fill them up with compound, or would he refrain from doing so for fear of bursting the lead sheath?

Mr. C. F. Bolton: Dr. Dunsheath has propounded a

* British Patent No. 416695.

rather difficult problem to the author. It is the problem met with particularly in traction work where feeder cables are not laid underground but are carried alongside the railway track. Such cables may reach very high temperatures in the summer and very low temperatures in the winter, which result first in a very high pressure and then in a vacuum. The following figures for such a cable, operating at 33 kV, are of interest. In July at 8 a.m. when the air temperature was 66° F. and the joint temperature the same, a vacuum of 13 in. was recorded on a joint. On the same day at 2.30 p.m. the air temperature was 81° F., the joint temperature 86° F., and the pressure had risen to 70 lb. per sq. in. The result, of course, is that the joint, and also the cable sheath, are distended and may possibly burst. In any case there is a migration of compound under vacuous conditions from the joint into the now greater volume inside the cable sheath, and the problem is whether in winter one should open up joints and add more compound. If this is done, a vicious circle may be started which will make the pressure conditions during the next summer much worse; if it is not done, the loss of compound and vacuous condition in winter may result in breakdown of the joint. In the case of the cable in question the solution of the problem was found to be the erection of a form of sun shielding to prevent the high pressure developing, and that solution was very successful.

In Section (4) (*b*) (iv) the author says: " With fluid filling it is advisable to examine the compound level, say, a year after installation, and subsequently according to the level last found." I quite agree with this. I have known cases where there has been quite serious loss of compound, and I feel that some provision for expansion at the sealing-end should always be provided, but to take cables out of commission to arrange for this to be added at a later date is a very serious matter. I should like to ask the author whether he knows of any investigation into the possibility of using glass sealing-end insulators, so that the compound level can be readily observed.

There is a point in connection with jointing materials, particularly for sealing-ends, which I should like to mention. Some manufacturers have used a cork jointing material with a linen insert; this practice is most dangerous. I have known cases where as much as half a cupful of water has been taken out of a 33-kV sealing-end insulator. This water has presumably entered through capillary attraction, and has caused subsequent breakdown. I agree with the author's statement that oil-resisting rubber makes an excellent joint.

[The author's reply to this discussion will be published later.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 4TH JANUARY, 1937

Mr. E. L. Davey: I should like to say something about the statement in the Introduction to the paper, referring to the future of the straight type of cable. It is well known that many new types of cable involving the use of the pressure principle are being developed by various cable makers, and it may be useful here to review the position of such cables. The necessity for the development of these highly stressed and hence smaller-dimensioned cables arises from the fact that the size of 132-kV straight-type cable is so great as to be impracticable, and there is every probability that in the near future 132-kV cables will be required in appreciable quantities in this country. When these new types of cables have been proved under service conditions they will probably supplant the straight-type cables for 66 kV, on economic grounds, and they may enter into the 33-kV field. It is important in this connection to note that some of these new types do not necessitate the use of reservoirs, etc., but can be operated in a manner similar to that of straight-type cables.

There are one or two points which I should like to make in connection with the joint shown in Fig. 5. It is stated on page 525 that the insulation of this joint is built up using paper tapes or a paper roll. In building up such a large radial thickness of impregnated paper I think it is very desirable to interleave open-lap bias-cut varnished-silk tape lappings at, say, every sixth layer, in order to produce a tight structure. This tape is extremely elastic compared with impregnated paper tape, and will tend to maintain the joint insulation in its initial condition when subjected to the influence of temperature cycles. A limit as to the quantity of silk tape that can be used in such a way is set by the risk of the thermal instability due to the steep slope of the dielectric-loss/temperature curve of the tape. Referring to the method of screening the joint, I think it is preferable to use flexible conducting tape instead of the tinfoil on the taper and the metallized paper over the cylindrical portion. This tape consists of graphite-coated varnished-silk tape, and its physical properties ensure a permanently close screening over the built-up dielectric.

With regard to the 33-kV joint shown in Fig. 7, stress cones are used at the screen termination on the 3-core cable, but none is shown on the single-core cables. This is not in line with the statement on page 525 regarding single-core cable terminations.

Turning now to Section (6), dealing with reliability testing, I cannot agree with the recommendation that the tests should be made at atmospheric pressure by leaving a filling orifice open. We are only concerned with the behaviour of the joint or terminal under service conditions and, to produce these, the length of cable attached to the joint or terminal should be comparable with that in service conditions, the joint or terminal should be sealed off, and the cable should be subjected to temperature cycles. For such a test twice working voltage should be continuously superimposed, power-factor/voltage tests should be carried out up to twice working voltage, and at the end of the test the joint or terminal should be dissected.

It is necessary and desirable that the joint and terminal should withstand a test of 4 times the working voltage for, say, 15 minutes, but a good deal more can be learned about joint and terminal design if power-factor/voltage

measurements are carried out on the various component portions. For instance, the stress cones can be lightly insulated from the sheath, etc., and insulated connections can be brought out for Schering-bridge measurements. In a similar way an insulated metallic cylinder can be arranged over the built-up dielectric over the ferrule and chamfered trims. It is possible by these methods to detect ionization or discharge at voltages well below the breakdown voltage, and the comparison of designs on this basis is better than on the basis of the breakdown test, in which, owing to the high value of the voltage used, factors enter which are not necessarily present under service conditions.

Mr. R. F. D. Milner: I should like to have the author's opinion as to the best pouring temperature for resin-mineral-oil compound.

With regard to the terminating boxes, I should like to know whether the author can give any indication of the breakdown voltages for that part of the insulator which is under compound. Can he confirm that a value 50 per cent in excess of the outside flashover voltage is a reasonable figure? The terminating box shown in Fig. 12 is to my mind weak in that the filling compound would have the greatest difficulty in obtaining access to the inside insulator. I should also like to question the efficacy of the washers on which the watertightness of the box seems to rely. Turning to the indoor terminal box shown in Fig. 13, I am not quite clear how moisture is prevented from gaining access to the interior of the box via the strand. Does the author rely solely on the compound filling?

In his slides dealing with the question of expansion joints it appeared to me that in every instance compression joints were called for rather than expansion joints.

My last point refers to Fig. 16(*e*), where moulded insulation is shown under the stress cone. It seems quite probable that the permittivity of the moulded insulation will differ from that of the paper, plus compound, and I should expect that an increased potential gradient would result from it.

Mr. J. H. Pirie: It is reassuring to read the author's statement in the Introduction to the effect that it is now possible to make joints and terminations of an electric strength equivalent to that of the cable. I would ask him, however, whether his statement is not a little too modest, as it should be possible to make joints and terminations superior in electric strength to the cable, since the present-day design of cables is continually improving. Also a greater factor of safety is required with these accessories where the human element has to be allowed for, e.g. in the building-up of reinforced insulation by the jointer, which is often done under adverse conditions out of doors, and cannot equal in quality the cable insulation applied under factory conditions. The extra expense entailed in achieving this object on a long transmission line is justified on the score of reliability, while at the same time it is desirable to keep the design as simple as possible so as to allow work to be done both quickly and easily by the jointer. In this connection the joint in Fig. 3 is one of the simplest shown in the paper, but has the restriction that a setting compound must be used to fill the box. In the other types of joint, paper wrappings are used in which one may not always be sure the paper is fully impregnated or tightly enough wrapped on to the cable to exclude all void spaces.

In the simple and very clean design of sealing end shown in Fig. 15, could the author explain why the impregnated-paper tube and lead-wire stress control are applied so high up inside the porcelain? By dropping the former the equipotential lines controlled by the base-plate and arcing ring may be more smoothly graded off on the free surface of the cable insulation.

Dealing with the problem of expansion on a 33-kV cable, the conductor and lead sheath at operating temperature under normal current rating will distend approximately an equal amount and therefore do not require any special type of flexible connector if the lead sheath is free to move. On heating lower-voltage cables in ducts, however, the lead sheath will expand more than the conductor, so that greater provision should be made for sheath expansion rather than conductor expansion as shown in Fig. 11. In the case of a cable buried direct in the ground the assumption that the weight of soil above holds the sheath rigidly in position should apply to the conductor as well.

I regret that the author does not deal more fully with the standard methods of testing joints and sealing ends. The arbitrary specification of 4 times working voltage applied for 15 minutes is so far removed from operating conditions that it is almost useless, and in place of it the impulse flashover of the sealing end might be more usefully specified, together with the behaviour at working voltage with a superimposed high-frequency voltage to simulate line conditions.

Mr. O. C. Waygood: Can the author give the approximate cost of making these joints, as a percentage of the cost per mile run?

[The author's reply to this discussion will be published later.]

DISCUSSION ON

"RECENT DEVELOPMENTS IN TELEGRAPH TRANSMISSION, AND THEIR APPLICATION TO THE BRITISH TELEGRAPH SERVICES"*

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 1ST FEBRUARY, 1937 †

Mr. H. Faulkner: The paper indicates a change which seems to be going on in many different branches of the electrical industry, namely that from direct current to alternating current. It is rather surprising to me that, although we have made this change as far as the circuits are concerned, we have not yet been able to change over the little motors which drive the teleprinters. It is necessary that these motors should run at a constant speed, and the stroboscopes and synchroscopes which are used to check the speed could be eliminated if the constant frequency produced by the grid system could be utilized, as is done in the case of electrically-controlled clocks. Perhaps the authors would tell us what progress has been made in this direction.

The system of voice-frequency telegraphs which was produced for use between London and the Leafield radio station is entirely free from relay contacts. Ordinary Wheatstone transmitters were used, but in order to key the voice-frequency circuit static relays, which have since been adopted as standard on our ordinary inland system, were developed. The voice frequency, having been keyed by the static relay, reaches its termination and after filtration operates a system of valves which acts as a relay and produces a negative bias on the grids of the valves in the early stages of amplification in the valve transmitters. In the previous systems in which ordinary telegraph relays were used trouble was experienced by the foreign stations in receiving clear signals, and many requests were received to change the transmitter. When this valve-operated device was installed no further trouble was experienced, and the receiving stations were able to receive at far higher speeds than previously. I should like to ask the authors whether all the relevant factors have been taken into consideration in deciding against thermionic relays. It will be seen from the authors' curves that the effect on maintenance costs of using a static relay instead of a mechanical relay is considerable, and the effect on service must be even greater.

Mr. H. G. S. Peck: One of the most interesting features of the new designs of telegraph equipment described in the paper is that the changes have not resulted in an increase in the speeds of telegraphy over the individual wires. The teleprinter, which is now the standard instrument, has a speed of transmission which is quite moderate compared with that of the Wheatstone instrument. The advantages gained are that the whole system is made more robust and more reliable, the operation of the instruments is rendered more simple, and the same classes of amplifiers and repeaters can be used for telegraphy as have been designed for telephony. It is no longer necessary to design special conductors for telegraphs; the telegraph conductor existed first, but now the telephone conductor has ousted the telegraph conductor. It would be very interesting to have some figures showing the traffic capacity and miles of wire for the cable system which previously existed for telegraphs (Fig. 1) as compared with the voice-frequency channels now in use for telegraphy (Fig. 2). I am not sure that all these changes have resulted in a decrease in the length of wires for transmitting the same amount of information.

In the Introduction the authors say that one of the advantages gained from these new methods is that the whole of the subsidiary and testing apparatus has been removed from the telegraphist's desk, but I notice that recently there has been a tendency to put back such apparatus. They refer also to the telex system, by which any telephone subscriber can have a teleprinter installed and by using the telephone network can exchange telegrams with any other subscriber who is similarly equipped. They refer to the possibility of there having been advantages in having set up an entirely separate system of exchanges and lines for telex; but it seems to me that the advantages must lie in having this telex system combined with the telephone system.

Mr. R. H. Rawll: I gather that when a teleprinter is installed there is only one connection to be made to the local power supply, and that, owing to the difficulties associated with a synchronous motor, a d.c. motor is incorporated in the apparatus. Thus, where only an a.c. supply is available, it is necessary to convert from alternating current to direct current. The supply to this lecture hall is direct current, and a special motor-alternator set has been provided to give alternating current, apart altogether from the Post Office apparatus. It seems that in this particular case we are converting the d.c. power supply to alternating current, which is again converted to direct current. I shall be glad to learn the reason for this double conversion.

Mr. C. J. O. Garrard: Mr. Peck complained that the large increase in the amount of apparatus for transmission and reception which has accompanied the introduction of the teleprinter service has not resulted in any great increase in speed of transmission as compared with those achieved with the Wheatstone transmitter. This may be true, but I think one must take into account the fact that with a teleprinter almost any girl who can use a typewriter can transmit as fast as a man

* Paper by Messrs. L. H. HARRIS, E. H. JOLLEY, and F. O. MORRELL (see page 237).
† Joint meeting with the Institution of Post Office Electrical Engineers.

who has had a long training with the Wheatstone transmitter. The increase in the complexity of the apparatus is thus balanced by the reduction of the skill required for its use.

It is not easy to understand why it should be so difficult to obtain an a.c. motor for the teleprinters. In the case of gramophones we do not have much difficulty in providing a constant-speed drive with an a.c. motor, and I cannot see why the authors do not use an a.c. universal motor governed in exactly the same way as existing d.c. motors are governed. It would be interesting to know what the difficulty is.

Messrs. L. H. Harris, E. H. Jolley, and **F. O. Morrell** (*in reply*): The advantages as regards speed control obtained by use of synchronous motors, mentioned by Mr. Faulkner, have been recognized and the question is being actively pursued. Examination of the question of the use of valve receiving relays has been made more than once and has shown that their field of use is restricted. For example, in the case of the multi-channel voice-frequency system such valve relays as are at present available would not give the necessary flexibility of output and would be uneconomical in respect of cost, space, and maintenance. Where the conditions are favourable, for example in the Telex convertor, they have been used with complete success. The case referred to by Mr. Faulkner, where the function of the relay is to modulate a radio transmitter, is another instance where the circumstances favour the use of valve receiving relays.

In reply to Mr. Peck, the maximum capacity of a 4-wire telephone trunk as used for multi-channel telegraphs is actually 1 800 words per minute (Wheatstone) in each direction without any restriction on its length, and the output using teleprinters is about 1 000 words per minute. This is considerably in excess of anything obtainable for the same weight of copper by direct current, and a substantial economy in respect of cable conductors has resulted from the introduction of voice-frequency working. Quite apart from this, the use of the teleprinter in conjunction with the voice-frequency system gives a much more stable service and permits an appreciable saving in operating costs.

There has been no change in the policy that the instrument tables should normally accommodate only apparatus directly concerned in the transmission of telegrams.

In reply to Mr. Rawll, it is not the general practice to convert to alternating current where the supply mains are direct current. This was done, in the case to which he refers, purely for convenience in setting up the demonstration apparatus.

Mr. Garrard compares the teleprinter-motor problem with that of the gramophone motor. The cases are, however, rather different in several respects. It is the conflicting requirements which make the teleprinter case difficult, and, further, it is not usual for the speed of gramophone motors to be controlled to the same degree of accuracy as a teleprinter motor. Universal a.c. motors have been used on the teleprinter but on account of the limitations of space, temperature-rise under the restricted ventilating conditions, and governing requirements, their performance was inferior to that given by d.c. motors.

SCOTTISH CENTRE, AT EDINBURGH, 23RD FEBRUARY, 1937

Mr. H. G. Davis: The paper is particularly interesting to me because it so happened that in 1932 I was in charge of the headquarters group responsible for setting up the new teleprinter private-wire service and the telex service. There were a lot of "teething" troubles when we started with the private service between London and Liverpool; but after a close analysis of faults and a good deal of further experimenting the early difficulties were gradually surmounted, and from the end of 1932 onwards the private-wire service expanded steadily. I am glad that the authors think there is a big future for the private wire service; there is little doubt that we shall soon have more teleprinters in private use than in the public service.

On the local end of a teleprinter private-wire circuit transmission from the renter's teleprinter is carried out on a single-current basis, and at the Post Office terminal this is converted into double current for transmission over the main link of the system. Fundamentally, wherever there is a transition from single- to double-current working, distortion must occur, and on this account double-current working throughout the circuit is to be preferred. In the paper, mention is made of rectifiers and rotary transformers for producing a double-current supply from the mains at a renter's premises, and I should be pleased if the authors could tell us how far these improvements have been applied to the private-wire services generally.

In regard to telex, the adoption of 1 500 cycles per sec. as the standard frequency is a big step forward. It has long been realized that a frequency of 300 cycles per sec. is too low to act as a satisfactory carrier for teleprinter signals, and the change to a 1 500-cycle carrier will result in greatly improved transmission generally. I should like to see 1 500-cycle transmission used for short lines in the public telegraph service and also on the longer extensions from the various multi-channel voice-frequency systems.

Perhaps the authors could give us details of any recent improvements in the teleprinter itself. For instance, has it yet been found possible to improve the transmission on teleprinters by means of electrical selection? With regard to switched telegraph systems, the progressive reduction in the cost of providing telephone channels raises the question whether it is possible now to consider the use for telegraph purposes of the telephone network with its ready-made switching facilities, instead of having multi-channel voice-frequency systems? The views of the authors on this subject would be of interest.

Mr. W. Cruickshank: The question which matters from the point of view of the general public is: How has the introduction of a.c. systems affected the transit time of the average telegram and the economics of telegraphs as a whole? In the past the chief charge on telegraphs was that of operating: for every 1s. paid for telegraphing some 9d. or 10d. was expended on operating.

The engineering charges were relatively small. The maintenance charges must have been increased to a very appreciable extent by the introduction of a.c. systems; to what extent have the operating costs been reduced?

To what extent has the telephone capital account been relieved by the handing-over of pairs formerly used for telegraphs, and how has the total telegraph-wire mileage been affected by the introduction of multi-channel systems?

The spread of the telex system is a fine thing from the point of view of the Administration. If we can get all large firms to send their own telegrams and pay the Department fair rentals for the lines, or even for the by-products of the physical circuits, it will be a very good thing from the Department's point of view.

Prof. M. G. Say: The human ingenuity displayed in telecommunications is truly amazing, and the advances in telegraphy in the last few years are not the least spectacular in this respect. How are the telegraph services carried on in Europe and America? I gather that several systems are in use, and should like to know in a few words how they compare in efficiency and modernity with the methods of the British Post Office.

The static relay shown in Fig. 13 is one of several recent circuits in which rectifiers are used to modulate or "key" an a.c. supply. Thus an analogous method, in which the impedance of a series transformer is varied by open- or short-circuiting its secondary by thyratrons, is used for welding control. It would seem, however, that there is no likelihood of the d.c. relay being displaced, on account of the universal characteristics of the d.c. link between channels of any two frequencies: this is obviously a most valuable property of the d.c. link.

If possible, I should very much like to have some details of the 18-channel generators. It does not look feasible at first sight to produce 18 frequencies without 18 different stator-rotor assemblies.

Mr. J. J. McKichan: It might be thought from the delicacy of the apparatus described in the paper that the service it would provide would be somewhat unreliable, but such is very far from being the case. As a matter of fact the voice-frequency system is uniformly more constant and reliable than d.c. telegraphy. The number of failures and troubles attributable to loss of synchronism and the difficulty of keeping the frequencies constant is very small indeed. Of course, the actual voice-frequency generators are situated at the trunk terminals in repeater stations, where there is an expert staff of transmission engineers. These men are able to spot and correct incipient troubles at an early stage, and the result is that the service is extremely reliable.

The developments in prospect are even more interesting than those which have been achieved. Automatic through switching of telegraphs will be introduced in the near future, and within a few years re-transmission at large centres like Edinburgh and Glasgow will have disappeared. The small office will then be able to send its telegrams direct to the terminal office. This facility will save two or three re-transmissions, and will speed up the transmission of a telegram.

The present paper is no doubt of particular interest to Mr. Cruickshank, who read a paper on "Voice-Frequency Telegraphs" before The Institution in 1929.* At that time a lot of thought was being given to possible methods of increasing the load on telephone and telegraph lines by the system known as "compositing." That system was put in the background as soon as voice-frequency methods developed as the result of enormous improvements in telephone transmission. The modern trunk telephone transmission system paved the way for the voice-frequency system.

Mr. C. A. Taylor: I should like to ask the authors whether they have anything to communicate regarding the automatic switching arrangements which will indicate the proposals for dealing with peak loads at switching centres. These peak loads may arise from two causes. One cause will be special events, some of which may be foreseen, and the facilities necessary can then be provided. There will be, however, some events of which little or no warning may be received. The other cause leading to congestion at a switching centre will be damage to a main cable which may throw out of use a large proportion of the circuits normally available.

If the system is going to function satisfactorily under these conditions, the second of which is the more serious, there will have to be a margin of circuit capacity to meet the requirements. Otherwise serious congestion will occur and as soon as the capacity of the equipment at any centre has been exceeded the service will deteriorate rapidly, owing to various teleprinter terminals endeavouring to dial their way through the centre to another terminal.

Under automatic switching conditions it would appear that a considerable amount of spare plant will have to be quickly available to meet these conditions, and account of this must be taken in estimating the cost of an automatic switching system. If the authors are in a position to state the results of their study of this problem, I am sure the information will be of interest.

Mr. J. W. Branson: There is just one question I should like to ask in connection with the extensions from the voice-frequency terminals, which according to the paper are to be worked on a d.c. basis. Of course this may be only a temporary phase, but it occurs to me that some of these extensions will be of considerable length and that there is the possibility of special arrangements to meet emergency traffic being required to places near the distant offices. Would it be possible to use the 1 500-cycle teleprinter No. 7 superimposed on the d.c. circuit? This would help in those cases where the provision of an additional channel to meet unexpected demands is difficult or quite impossible otherwise.

Mr. W. McWalter: Has the possibility been considered of tapping the main circuit at intermediate points along the route and using, say, half a dozen frequencies between one terminal and the intermediate point and another half dozen or dozen between the two terminals? This seems to me to be a possibility, and it would provide for the smaller stations on the route of a main circuit.

Messrs. L. H. Harris, E. H. Jolley, and F. O. Morrell (*in reply*): Mr. Davis refers to the inherent disadvantages in converting from single-current to double-current working at the local end of a private wire. Double-current working using rectifiers or rotary trans-

* *Journal I.E.E.*, 1929, vol. 67, p. 813.

formers is now employed on the local end when the main link is a voice-frequency channel, and this practice may eventually be extended to those cases where the main link is a direct-current channel.

The Telex system gives only a simplex service and would not therefore be suitable for duplex extensions from the multi-channel system. At present the direct-current method adopted appears to be the most economical. This requires no additional apparatus on a short extension and simply a relay on a long extension, apart from the equipment required at the out-station to supply the operating currents.

With regard to improvements in the teleprinter, several changes have recently been introduced on the receiving mechanism which give an increase of margin and should make for greater reliability. The behaviour of machines under working conditions is constantly under review, and improvements in the design of various parts are undertaken where it is shown that an improvement in service can be obtained. There have been no developments in respect of a teleprinter with electrical selection, and so far as is known a teleprinter of this type would be at least as expensive to construct as the mechanical type, without any appreciable reduction in operating costs. Very definite advantages must exist in order to justify complicating maintenance problems by introducing new types of machines.

A system such as Mr. Davis suggests, making use of a whole telephone circuit for one telegraph channel as against 18 telegraph channels, would be too extravagant in line costs to merit its consideration as an alternative to the switching system now under investigation.

Contrary to Mr. Cruickshank's remarks on maintenance charges, the introduction of voice-frequency working has reduced considerably the annual cost of a telegraph channel as compared with the costs under the old methods of working. Saving of costs on the operating side have also been effected because the only equipment requiring attention in the instrument room is the teleprinter itself. In addition, owing to the comparative cheapness of a voice-frequency channel it has been possible to provide circuits on a more liberal basis, so obviating a certain amount of re-transmission of telegrams, with a consequent saving in costs.

Telephone circuits used for telegraphy are charged to the latter service on a rental basis. The total Post Office wire mileage in use for telegraphs at December, 1936, was 239 000, including 41 000 wire-miles of 4-wire trunks used for multi-channel systems. Owing to the considerable increase in the number of teleprinter channels, a fair comparison cannot be made with the wire mileage before the introduction of voice-frequency working, but to provide the existing services on a direct-current basis would require a mileage of 520 000. This comparison must also be made with reserve on account of the loading coils, repeaters, and terminal equipment, required for voice-frequency working.

In reply to Prof. Say, in no other country has the teleprinter been introduced into the public telegraph service to the exclusion of other methods to anything like the extent that has been the case in the British Post Office, nor has any other country so complete and uniformly modern a voice-frequency network as Great Britain. Both the teleprinter and voice-frequency working are largely used in the United States, and to a lesser extent in Germany. Other countries also are using them to a limited extent. The question is, however, largely affected by geographical considerations, and the extent to which services are provided to sparsely populated areas remote from the main centres.

The multi-frequency generator is excited from a common d.c. field and has 18 separate rotors in the form of toothed iron discs mounted in line on a common shaft. The number of teeth depends on the frequency to be generated. Individual windings are provided on the stator for each of the frequencies.

While we are not in a position to give detailed information in reply to the points raised by Mr. Taylor regarding traffic overloads on a switched telegraph service, the following general observations can be made in this connection. Any telegraph system should be prepared to face up to emergencies which can be reasonably anticipated without excessive disturbance to the disposal of traffic. For example, it is the practice to cover the possibility of complete failure of a main cable route by the provision of alternative routes. In the design of the telegraph switching system the necessity for catering for emergencies such as those mentioned has not been overlooked, and whatever the ultimate arrangements will be it is probably safe to say that in no essential respect will the service under emergency conditions be inferior to that given under similar emergency conditions on the present system.

The expedient, mentioned by Mr. Branson, of the provision of a teleprinter extension circuit superposed on a d.c. circuit using the Telex system of working might possibly be applied in certain circumstances under emergency conditions, but no general application of this method can be envisaged.

The scheme of dropping certain channels at intermediate points, referred to by Mr. McWalter, is in use in certain cases in Europe. The London–Glasgow–Belfast 18-channel system mentioned on page 237 of the paper was worked in this way, 6 channels being worked London-Belfast and 12 channels London–Glasgow. This method of working has, however, been abandoned in Great Britain owing to the non-flexible filter arrangements and the difficulty of providing alternative routings under cable breakdown conditions as mentioned on page 247 of the paper.

THE EXTERNAL CHARACTERISTIC OF A DIODE RECTIFIER*

By E. B. MOULLIN, M.A., Member.

(*Paper first received 4th July, and in final form 3rd December*, 1936.)

SUMMARY

The paper discusses the behaviour of a rectifier system consisting of a thermionic tube, output load, and smoothing condenser. An equation is derived relating the d.c. output current and output voltage, and this equation is verified experimentally. The dependence of the mean output voltage and ripple on the size of the reservoir condenser is discussed and examined experimentally. The efficiency of the rectifier is expressed as a function of the voltage-drop on load, and tables are given which show the power factor of the system and also the effective heating current in both windings of the supply transformer. The effect on the output voltage of the leakage inductance of the transformer is examined experimentally and discussed in general terms. It is shown that the resistance of the transformer is competent to increase appreciably the voltage-drop on load.

Finally it is shown that the analysis is valid in the main for bi-phase half-wave rectification, including the cascade system used by J. D. Cockcroft.

(1) INTRODUCTION

The exact analytical derivation of the equation of the external characteristic of a diode rectifier is very intricate, but for the limiting case of a very large reservoir condenser it is exceedingly simple. This solution is of practical value, because experience shows that the external characteristic is sensibly independent of the size of the reservoir condenser, provided it is large enough to justify its function of reducing the ripple. This paper presents the said simple solution, discusses its limitations, and also contains an experimental verification performed with a small diode thermionic tube.

(2) THE RECTIFIER CIRCUIT AND ITS CYCLE OF OPERATION

Fig. 1 represents diagrammatically a half-wave rectifier circuit. S is a source of sinusoidal voltage of any magnitude, say 6 kV; D is a diode thermionic valve (the filament transformer is not shown). Direct current

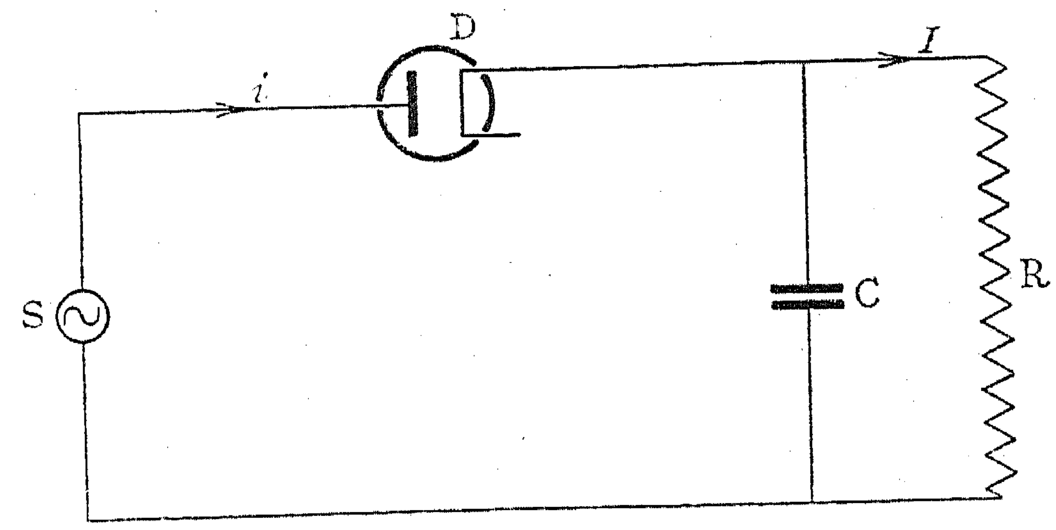

Fig. 1

is supplied to the load R, which is shunted by a capacitor C whose purpose is to reduce the magnitude of the fluctuations of current through R; the capacitor is exactly analogous to an air bottle in the delivery pipe of a single-acting reciprocating pump. Current passes through the diode in pulses whose duration is usually much less than half the periodic time of the alternating supply S. Part of such a pulse passes at once through R and part is stored in C, to be discharged through R during the interval between successive pulses. When the rectifier plant is in a steady state of operation the regime is illustrated by the oscillogram reproduced in Fig. 2, in which three half-waves of applied voltage are shown. The curve CABCABC depicts the wave-form of p.d. across the load resistance R. At some epoch in the voltage cycle, represented by "b" in Fig. 2, conduction ceases in the diode and subsequently the current

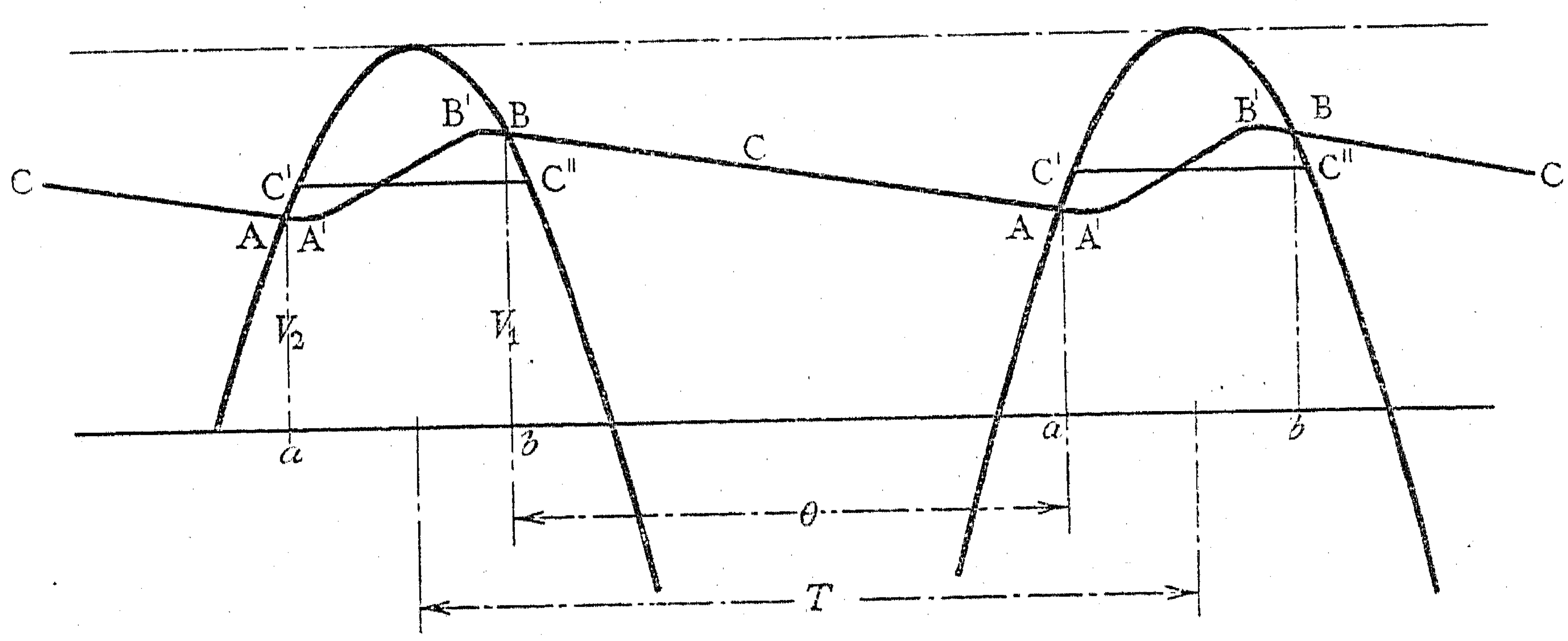

Fig. 2

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

flowing through R is supplied from the charge stored in C. When the p.d. of the condenser has fallen to some value V_2, the diode again becomes conducting at epoch " a." At a time shortly after " a " the condenser ceases to discharge and continues to charge until a time shortly before " B." The form of the portion A′B′ of the curve of output voltage is shown by oscillograms to be always substantially straight: its exact form will not typical: it is characterized by a very long straight portion, the slope resistance in this case being 750 ohms. At the origin the slope is 2 300 ohms. In this analysis the diode will be deemed to have one or other of the simplified characteristics illustrated in Figs. 5(*a*) and 5(*b*); it will appear that the analysis valid for characteristic (*a*) is valid also for characteristic (*b*) after a very obvious adjustment has been made.

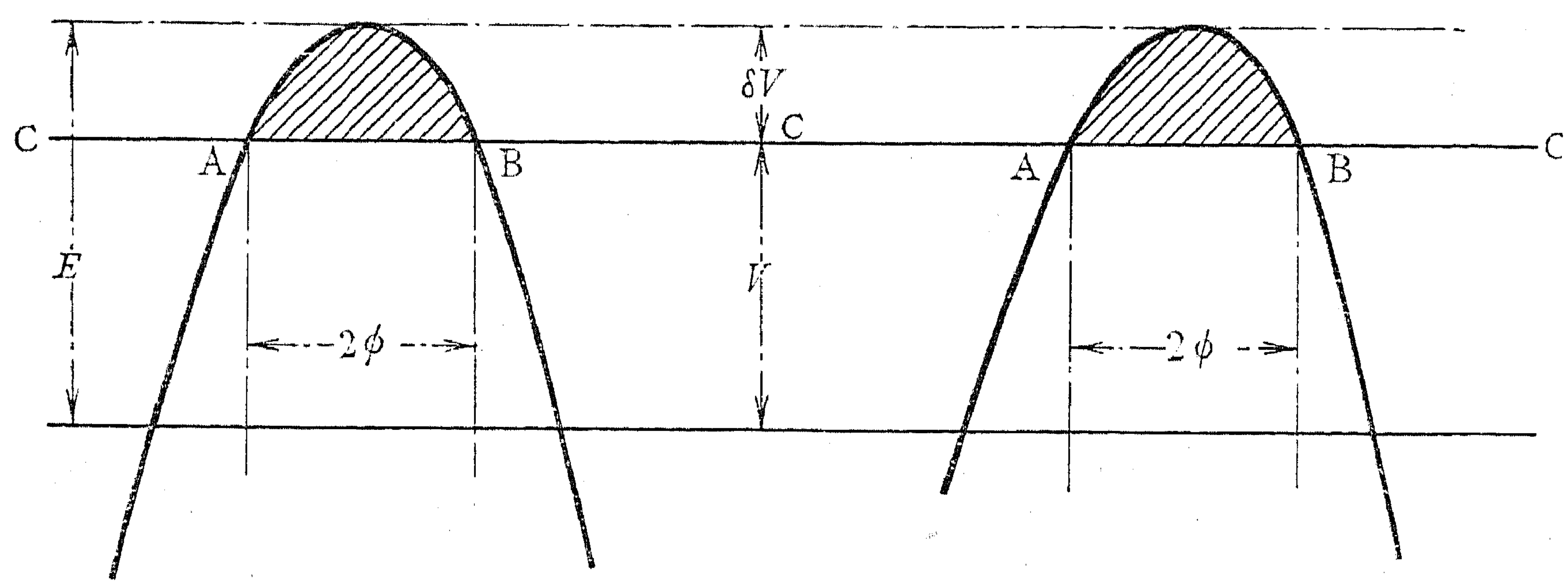

Fig. 3

be examined analytically. During epochs such as " ba," the diode is not conducting and the output voltage is expressed by the equation

$$v = V_1 \epsilon^{-\frac{1}{RC}t}$$

If the time-constant RC is large compared with T, V_2 will be not much less than V_1, for

$$\frac{V_2}{V_1} = \left(1 - \frac{\theta}{RC} + \frac{\theta^2}{2R^2C^2} \cdots\right)$$

Thus if $RC > 10\,T$, it is still greater than 10θ and then

$$\frac{V_2}{V_1} = \left(1 - \frac{\theta}{RC}\right)$$

to an accuracy closer than $\frac{1}{2}$ %.

Then
$$\frac{V_1 - V_2}{V_1} = \frac{\theta}{T} \cdot \frac{T}{RC} \quad . \quad . \quad . \quad . \quad (1)$$

If $RC = 10T$, the fractional difference between the greatest and least output voltage is less than 10 %. The condition $RC = 10T$ is equivalent to the statement that the reactance of the condenser at the supply frequency is equal to $R/63$. Equation (1) is the well-known formula for estimating the magnitude of the ripple in the output voltage.

If C is very large, the curve CABCABC in Fig. 2 will approach more and more closely to a horizontal straight line. The relation between mean output current and mean output voltage will now be calculated in the circumstances when R is shunted by an exceedingly large capacitance. The effect of the finite magnitude of C will be discussed later.

This regime of operation is depicted in Fig. 3. The diode is conducting during the intervals during which the applied voltage exceeds the output voltage V, i.e. in the duration of the caps shown shaded in Fig. 3. It is now necessary to consider the characteristic of the diode. The characteristic of a certain diode thermionic tube rated for an anode dissipation of 1 kW is shown in Fig. 4. The form of this particular characteristic is

(3) THE EQUATION OF THE EXTERNAL CHARACTERISTIC

Let A be the area of the shaded cap of the sine curve in Fig. 3. Then the quantity of electricity passing through the diode, having a characteristic according to Fig. 5(*a*), is A/ρ and hence the mean current during the whole cycle is $I = A/(2\pi\rho)$.

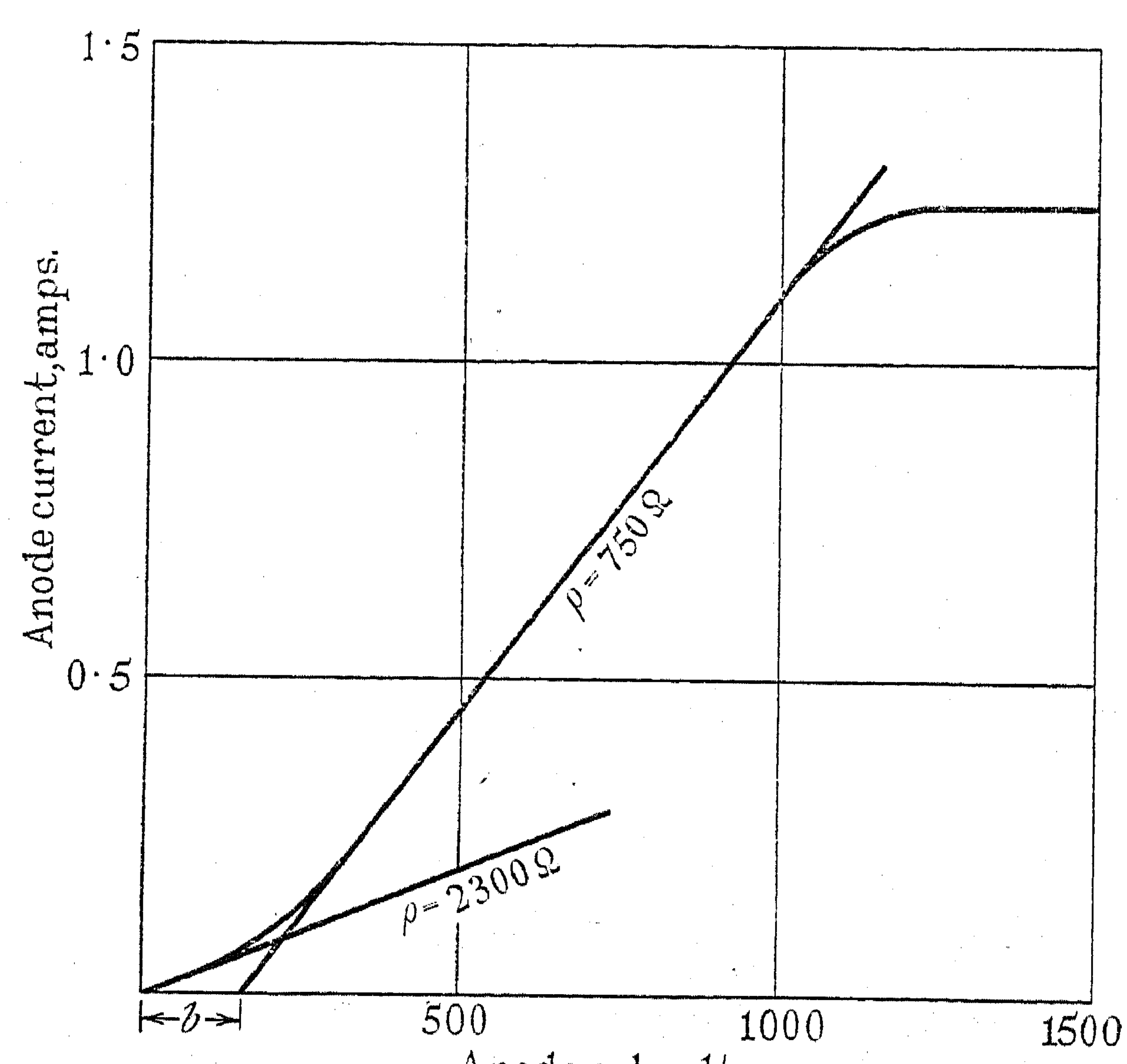

Fig. 4.—Typical characteristic of thermionic diode.

Using the notation described in Fig. 3, it follows that

$$\begin{aligned} A &= 2(E \sin\phi - V\phi) \\ &= 2E(\sin\phi - \phi\cos\phi) \\ &= \frac{2E\phi^3}{3}\left(1 - \frac{\phi^2}{10} + \frac{\phi^4}{280} \cdots\right) \quad . \quad . \quad . \quad (2) \end{aligned}$$

Also

$$E - V \equiv \delta V = E(1 - \cos\phi)$$
$$= \frac{\phi^2 E}{2}\left(1 - \frac{\phi^2}{12} + \frac{\phi^4}{360}\dots\right) \quad . \quad (3)$$

Therefore $$\frac{A}{\delta V} \simeq \frac{4}{3}\phi\left(1 - \frac{\phi^2}{60} - \frac{\phi^4}{1\,680}\right) \quad . \quad . \quad . \quad (4)$$

$= \frac{4}{3}\phi$, to an accuracy of 2 per cent even when

$$\phi = \pi/3 \quad . \quad . \quad . \quad . \quad . \quad . \quad (4a)$$

This approximation is equivalent to treating the sinusoidal cap as a parabola. It follows from (3) that

$$\phi^2 \simeq \frac{2\delta V}{E}\left(1 + \frac{\phi^2}{12}\right)$$

Therefore $$\phi \simeq \left(1 + \frac{\phi^2}{24}\right)\sqrt{\left(\frac{2\delta V}{E}\right)} \quad . \quad . \quad . \quad (5)$$

Inspection of the diode characteristic, Fig. 4, shows that it could not suitably be represented by Fig. 5(*a*) for values of δV greater than about 150 V. For values of δV between 250 and 1 000 V the characteristic may be represented by Fig. 5(*b*). If the characteristic be so typified, then clearly the voltage-drop will exceed that calculated from (6) by a constant amount b, and accordingly (6*a*) will now take the form

$$\frac{\delta V}{E} = 2\cdot 22\left(\frac{\rho I}{E}\right)^{2/3} + \frac{b}{E}. \quad . \quad . \quad . \quad (7)$$

(*Note*: It is perhaps worth emphasizing here that there is no relation between the 3/2-power law of equation (6*a*) and the well-known 3/2-power law which defines the characteristic of a space-charge-limited idealized diode.)

It is clear from the manner of deriving equation (6) that the external characteristic is dependent on the wave-form of applied voltage. It can readily be shown

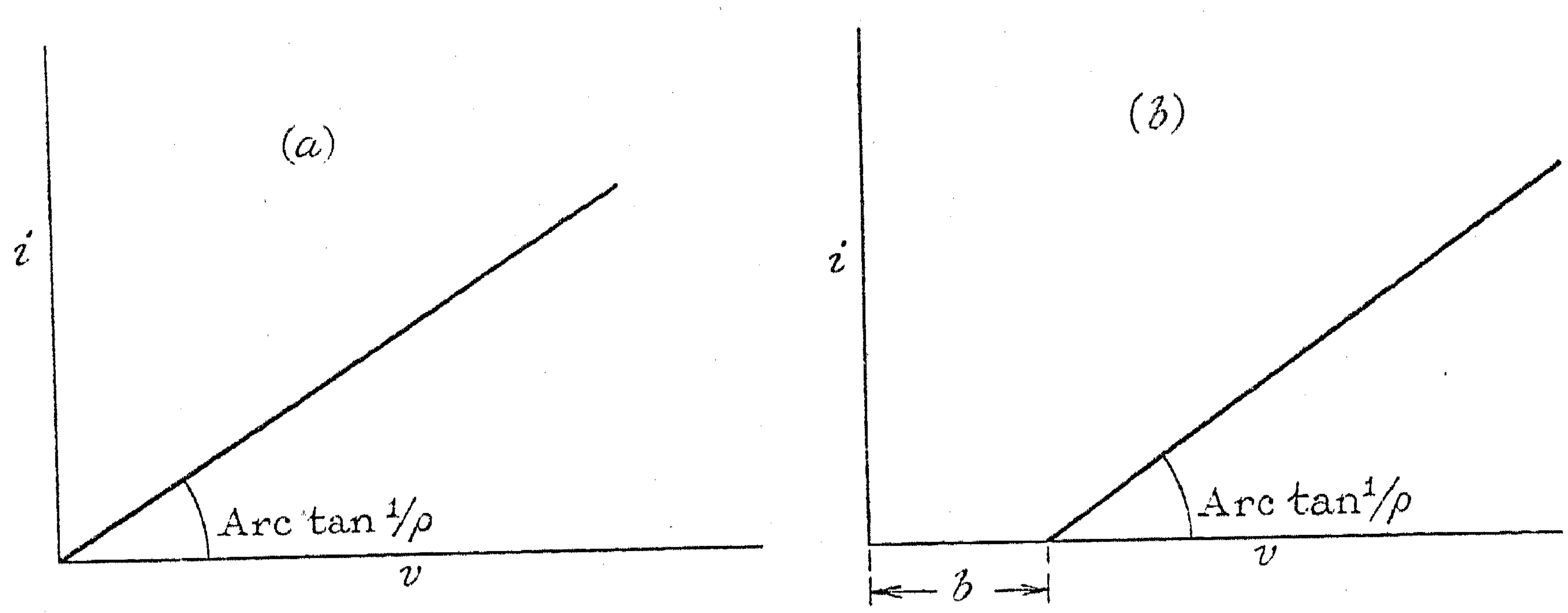

Fig. 5

Combining (4) and (5), it follows that

$$\frac{A}{\delta V} \simeq \frac{4}{3}\left(1 + \frac{\phi^2}{40}\right)\sqrt{\left(\frac{2\delta V}{E}\right)}$$
$$\simeq \frac{4}{3}\left(1 + \frac{\delta V}{20E}\right)\sqrt{\left(\frac{2\delta V}{E}\right)}$$

On substituting $A = 2\pi\rho I$, it follows that

$$\left(\frac{\delta V}{E}\right)^{3/2} \simeq \frac{3\pi\rho}{2\sqrt{2}}\frac{I}{E}\left(1 - \frac{\delta V}{20E}\right) \quad . \quad . \quad . \quad (6)$$

When $\delta V/E = 1$ it is readily shown that the exact relation between E and I is $\pi\rho I/E = 1$, whereas the value calculated from (6) is $3\cdot 17\,\rho I/E = 1$. It therefore follows that equation (6) is correct to closer than 1 % for all values of $\delta V/E$. There is, in fact, little practical interest in values of $\delta V/E$ greater than $\frac{1}{2}$, and accordingly it is sufficient to write

$$\left(\frac{\delta V}{E}\right)^{3/2} = 3\cdot 34\frac{\rho I}{E} \quad . \quad . \quad . \quad . \quad (6a)$$

When $\frac{\delta V}{E} = \frac{1}{2}$ it follows that $I = 0\cdot 354\frac{E}{3\cdot 34\rho}$.

Thus the voltage-drop is 50 % when the current is 35 % of the current which would result on short-circuit if the valve were not then limited by temperature saturation.

that with a rectangular wave-form of maximum value E the equation of the external characteristic will be linear and given by

$$V = E - 2\rho I \quad . \quad . \quad . \quad . \quad . \quad (8)$$

If the wave-form were an isosceles triangle of maximum value E, then the external characteristic would be parabolic, having the equation

$$\left(\frac{\delta V}{E}\right)^2 = \frac{4\rho I}{E} \quad . \quad . \quad . \quad . \quad . \quad (8a)$$

Fig. 6 shows the predicted external characteristic for the diode described by Fig. 4 when used as a rectifier with an applied p.d. of 1 410 volts r.m.s. (2 000 V maximum). The curve AB is derived from equation (6*a*) using $\rho = 2\,300$ ohms. The curve CD is derived from equation (7) using $\rho = 750$ ohms and $b = 150$ volts. The two curves cross at E, where $\delta V = 250$ volts, and the current is $0\cdot 015$ A, which is only about 2 % of the nominal short-circuit current. Consequently the range over which (6*a*) is valid is so small as to be negligible, and substantially the whole characteristic is described by equation (7). Though the nominal short-circuit current for $E = 2\,000$ and $\rho = 750$ ohms is $0\cdot 8$ A, in practice the short-circuit current would be much smaller, for Fig. 4 shows that the valve saturates when the current is $1\cdot 25$ A, and hence the short-circuit current

would necessarily be less than 0·625 A. Limitation by saturation would make the characteristic invalid for currents greater than 0·25 A. This, however, is a limitation of the diode and not, strictly speaking, of the analysis. Had E been chosen at 1 000 instead of 2 000 V, the characteristic would have been valid up to short-circuit. The valve is rated for 8·5 kV (r.m.s.); hence, if the saturation region is just not to be reached, δV must not exceed 1 000 volts and then $\dfrac{\delta V}{E} = \dfrac{1\,000}{12\,000}$. By the use of equation (7) it follows that then the current would be 0·09 A and the output would be

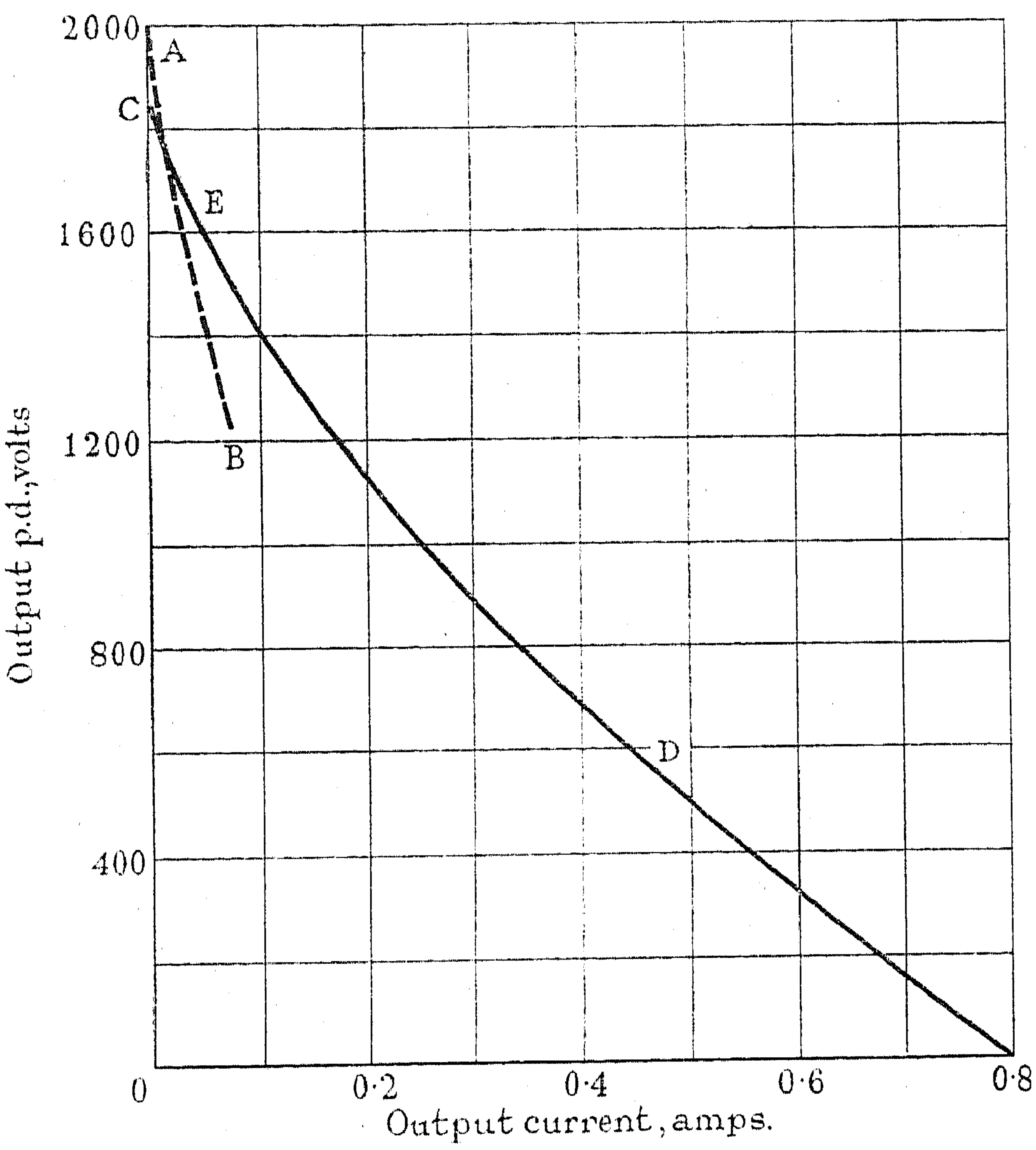

Fig. 6.—External characteristic of rectifier using valve of Fig. 4, with $E = 2\,000$ V.

0·99 kW. For a given output current, equation (7) may be written in the form

$$\delta V = b + kE^{1/3}$$

Thus, doubling the a.c. voltage will increase δV for a given current by less than 25 %: hence, for comparatively small values of $\delta V/E$, the output voltage is very nearly proportional to the input voltage.

(4) EFFECT OF A FINITE RESERVOIR CONDENSER

Equations (6), (7), (8), and (8a), are correct in the limiting, though unpractical, condition of an infinite reservoir condenser. Experiments with a rectifier show that, with a given load, T/RC must be approximately unity before the output voltage is reduced by 5 %. Since the ripple is then about 32 %, it may be concluded that the output voltage is sensibly independent of the size of the reservoir condenser, provided this is such as to make the ripple less than, say, 20 %. The reason for this becomes apparent on reference to Fig. 2, for only when V_1 and V_2 are notably different will the cap area AA′BC′A be appreciably different from the area of the cap above the horizontal line C′C″. The practical value of an expression relating V to the size of the reservoir condenser does not justify the labour of producing it. If the wave-form of applied voltage has a very flat top, oscillograms show that the curve of output voltage has a cog on it at the points A and B. This cog cannot be removed appreciably by increasing the size of the reservoir condenser. The reason for this cog is readily understood by considering the limiting case of a rectangular wave-form. For then the difference between the applied p.d. and the output voltage at the instant when conduction starts would have to be shared between the drop in the valve and an instantaneous rise of output p.d. In fact the size of the cog would be determined by the capacitance of the diode and the inductance of the leads, and would depend very little on the reservoir condenser.

(5) EXPERIMENTAL VERIFICATION

The external characteristic is shown in Fig. 7 of a rectifier using the small diode having the characteristic shown in Fig. 8. In the notation of Fig. 5(b), $\rho = 1·22$ kilohms and $b = 10$ volts for this diode. The upper curve in Fig. 6 is the external characteristic calculated from equation (6a). If $\log(\delta V - 6)$ is plotted against $\log I$, the result is a straight line of slope 1·55 over the range $I = 1$ to $I = 18$ mA, corresponding to $\delta V/E$ ranging from 14·2 % to 63 %. The appropriate value of b appears to be 6, whereas the intercept is 10; it is appropriate that the experimental value should be less than 10, because the true characteristic passes smoothly through the origin.

Oscillograms of the current-pulses showed curves symmetrical about the mid-ordinate and of form suggesting a parabola. It was verified that the height of these pulses was proportional to $(E - V)$ for values of $\delta V/E$ ranging from 31 % to 71 %.

(6) OUTPUT, EFFECTIVE RESISTANCE, AND EFFICIENCY, OF THE RECTIFIER

It follows from equation (6a) that the output power P_0 is related to the output p.d. V by the equation

$$P_0 = VI = \frac{V(E - V)^{3/2}}{3·34\rho E^{1/2}} \quad . \quad . \quad . \quad . \quad (9)$$

It follows from (9) that P_0 is a maximum, with respect to variations of V, when $V/E = \frac{2}{5}$.

The power input to the rectifier is obtained by integrating the product of an ordinate of the shaded cap in Fig. 3 with the corresponding ordinate of the applied voltage. If this is done, it follows that, in the notation of Fig. 3, the mean rate of input P_i is

$$\begin{aligned} P_i &= \frac{E^2}{2\pi\rho}(\phi - \tfrac{1}{2}\sin 2\phi) \\ &= \frac{E^2}{2\pi\rho} \times \frac{2}{3}\phi^3\left(1 - \frac{\phi^2}{5} + \frac{2}{105}\phi^4\right) \\ &= IE\left(1 - \frac{\phi^2}{10} + \frac{23}{4\,200}\phi^4\right) \text{ [from (2)]} \\ &= IE\left(1 - \frac{1}{5}\cdot\frac{\delta V}{E} + \frac{2}{175}\cdot\frac{\delta V^2}{E^2}\right) \text{ [from (5)]} \quad (10) \end{aligned}$$

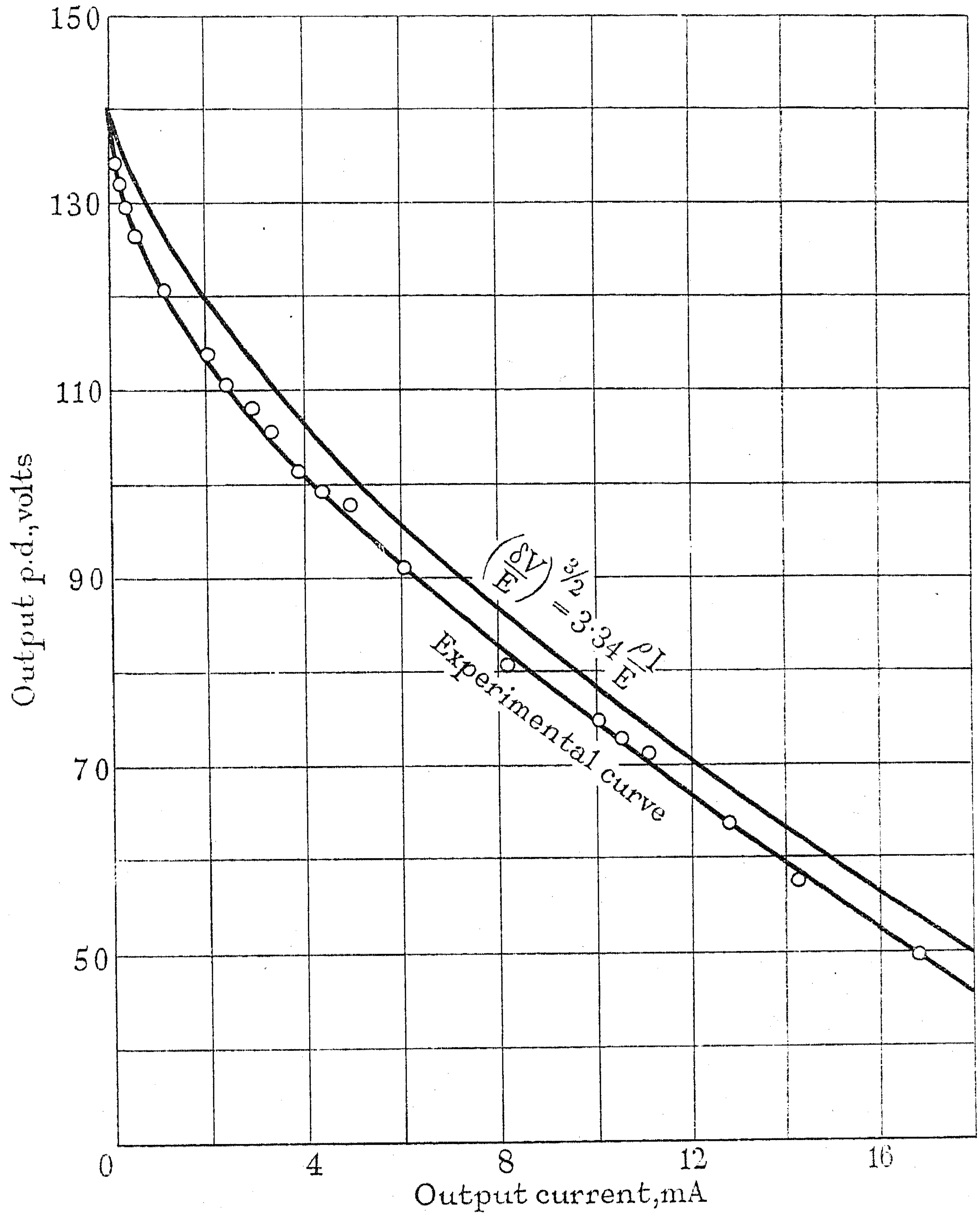

Fig. 7.—Predicted and experimental external characteristic of rectifier using valve of Fig. 8.

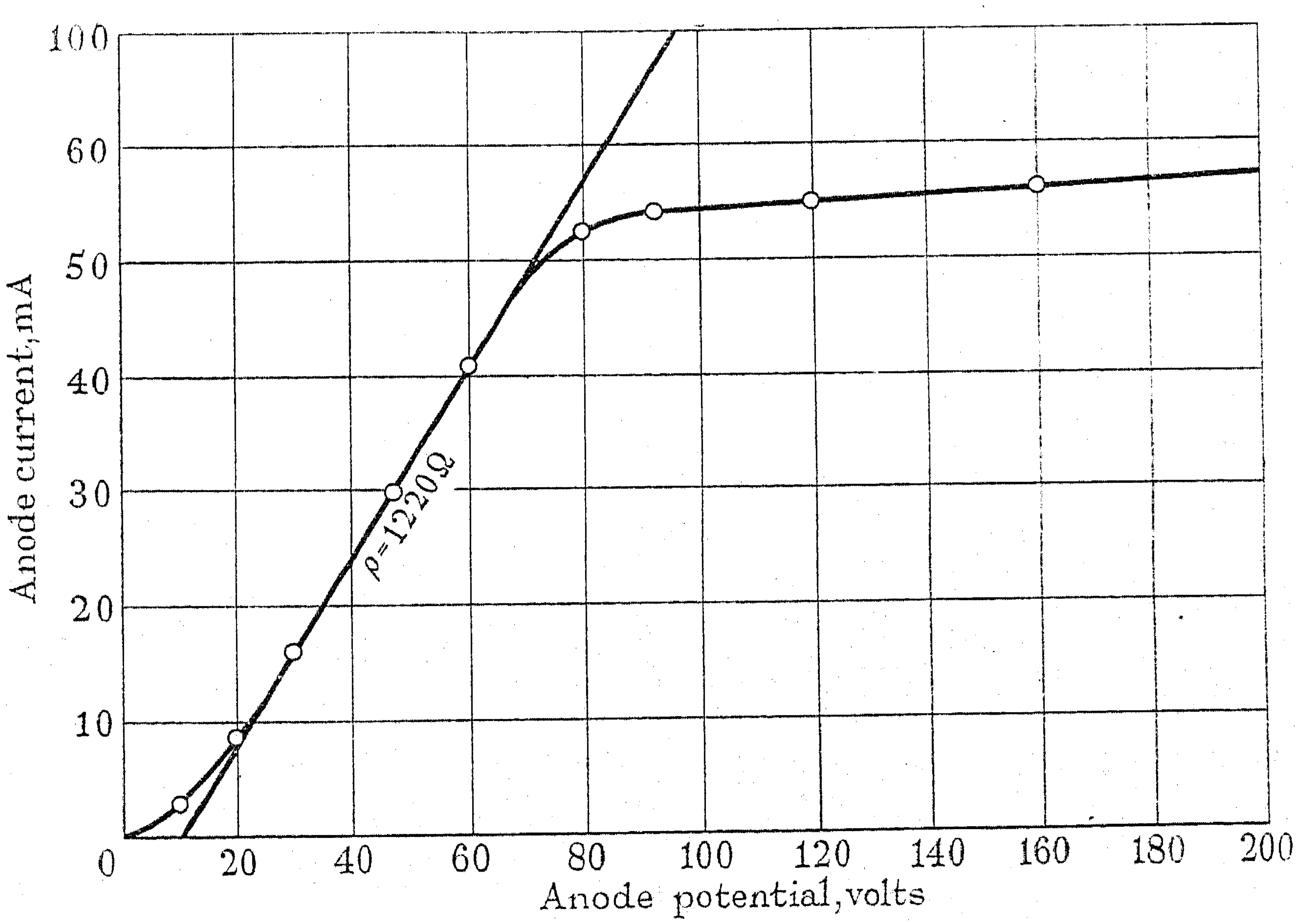

Fig. 8.—Characteristic of small thermionic diode.

It follows from (10) that the efficiency η is given by the expression

$$\eta = \frac{V}{E\left(1 - \frac{1}{5}\cdot\frac{\delta V}{E} + \frac{2}{175}\cdot\frac{\delta V^2}{E^2}\right)} \quad . \quad . \quad (11)$$

If η is plotted against V/E it will be found that the efficiency is sensibly a linear function of V/E within the range $V/E = 1$ to $V/E = 0\cdot45$, and can be expressed by the equation

$$\eta = 0\cdot11 + 0\cdot89V/E$$

From this it follows that the efficiency at maximum output is 46·5 %.

If the input current to the rectifier be expressed by the Fourier series

$$i = I + A\sqrt{2}\sin pt + B\sin(2pt + \lambda)\ldots$$

then it follows that $P_i = EA/\sqrt{2}$, since the higher harmonics contribute nothing to the mean input power.

We may now define the effective input resistance R' such that

$$R' = \frac{E}{\sqrt{2}A} = \frac{E^2}{2P_i} \quad . \quad . \quad . \quad . \quad (12)$$

Since P_i is related to $\delta V/E$ by (10) and since $V = IR$, it is possible to relate R' to R by the equation

$$R' \equiv FR$$

where F is a factor depending on V/E. It follows from (10) that

$$F \simeq 0\cdot6\frac{E}{V} - 0\cdot1$$

(7) MEAN SQUARE VALUE OF THE INPUT CURRENT

To estimate the heating which the rectifier load produces in the windings of the high-tension transformer supplying the voltage, it is necessary to calculate the mean square value of the current in both windings of the transformer. Let the current flowing through the tube be i at a given instant in the conducting period. Then, in the notation of Fig. 3,

$$i\rho = E(\cos\theta - \cos\phi) \quad . \quad . \quad . \quad (13)$$

On integration of i^2, it follows that

$$\text{mean } i^2 = \frac{\phi}{2\pi}\left(2 - \frac{3}{2}\cdot\frac{\sin 2\phi}{\phi} + \cos^2\phi\right)\frac{E^2}{\rho^2}$$

$$\simeq \frac{2\phi^5}{15\pi}\left(1 - \frac{4}{21}\phi^2\right)\frac{E^2}{\rho^2}$$

On substituting from equations (2) and (5), this becomes

$$\text{R.M.S. current} \equiv I_2 \simeq 1\cdot64I\left(\frac{E}{\delta V}\right)^{1/4}\left(1 - \frac{9}{280}\frac{\delta V}{E}\right)$$

$$\simeq 1\cdot64I\left(\frac{E}{\delta V}\right)^{1/4} \quad . \quad . \quad . \quad (14)$$

Some calculated and experimental values of I_2/I are collected in Table 1, and it may be seen that they are in close agreement.

It appears from Table 1 that if the rectifier is to deliver a steady current I, then the output winding of the transformer must be rated for a current some $2\frac{1}{2}$ to 3 times I. The r.m.s. current in the output winding must be much greater than I, for it consists of I together with the sinusoidal component A which supplies the output power and also the high harmonic components. The current through the input winding will have no steady component and will be substantially equal to the alternating components enlarged in the ratio of transformation. Thus if I_1 be the mean square current in the input winding, and x the ratio of transformation, then

$$I_1^2 = x^2(I_2^2 - I^2)$$

$$= x^2I^2\left\{2\cdot68\left(\frac{E}{\delta V}\right)^{1/2} - 1\right\} \quad . \quad . \quad . \quad (15)$$

If the resistance of the input winding of the transformer be R_1 and that of the output winding be x^2R_1, then

Transformer copper losses

$$= R_1(I_1^2 + x^2I_2^2)$$

$$= 2x^2R_1\left(I_2^2 - \frac{I^2}{2}\right)$$

$$= 2x^2R_1I^2\left\{2\cdot68\left(\frac{E}{\delta V}\right)^{1/2} - \frac{1}{2}\right\}$$

$$\equiv 2x^2R_1I^2Y^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Some values of I_1/xI, Y^2, and Y, are collected in Table 2.

Table 1

$\delta V/E$	0·05	0·1	0·2	0·3	0·5	0·7	1
I_2/I	3·48	2·91	2·45	2·32	1·95	1·78	1·56
I_2/I by experiment ..	—	—	2·4	2·3	1·95	1·75	—

Thus it appears that rectifiers designed to work at an efficiency round 90 % should be supplied by a transformer having a kVA rating which is about three times that of the load. If the transformer is built for the purpose then the two windings should have resistances which are in a ratio less than $x^2 : 1$.

The root-mean-square value xA of the fundamental component of the transformer input current I_1 may be obtained as follows, for, by definition of R',

$$A = \frac{E}{\sqrt{2}R'} = \frac{E}{\sqrt{2}FR} = \frac{E}{\sqrt{2}FV}I \simeq \frac{I}{\sqrt{2}(0\cdot6 - 0\cdot1V/E)}$$

The r.m.s. input current (ignoring magnetizing current) has been seen to be $I_1 = x\sqrt{(I_2^2 - I^2)}$. Thus the input volt-amperes are $E/\sqrt{2}\sqrt{(I_2^2 - I^2)}$, and the input power (ignoring iron and copper losses) is $EA/\sqrt{2}$. Hence the power factor of the rectifier plant will be equal to the ratio $A/\sqrt{(I_2^2 - I^2)}$. Some values of A/I and power factor are collected in Table 3.

Table 2

$\delta V/E$	0·05	0·1	0·2	0·3	0·5	0·7
I_1/xI	3·32	2·72	2·24	1·96	1·66	1·48
Y^2	11·5	8	5·5	4·4	3·3	2·7
Y	3·4	2·83	2·35	2·1	1·81	1·64

Thus it appears that the power factor of a rectifier working at an efficiency near 90 % will be of the order of 0·5.

(8) EFFECT OF INDUCTANCE IN SERIES WITH THE DIODE

If the input is provided by a transformer whose capacity is suited to the rectifier load, it is possible that the wave-form of voltage applied to the rectifier may be distorted appreciably. For the current-pulses pass through the leakage inductance of the transformer and thereby cause a voltage-drop which is not sinusoidal. The complete solution of the problem is intractable, but it is possible to estimate the order of the effect. Perhaps the problem is approached best by means of Fig. 9, which is an oscillogram showing the current-pulses and the voltage across an iron-cored inductance placed in series with the diode. The reactance of the inductance at the supply frequency (50 cycles per sec.) was 5 000 ohms. The load resistance was 18 000 ohms and the reservoir capacitance 11 μF. The symmetrical and shorter current-pulse was that obtaining when the series inductance was removed, the load resistance being unchanged. Calibration of the oscillograph showed that the maximum voltage-drop across the inductance was 22 V and the maximum voltage-rise 43 V, making a total of 65 V. The maximum value of the sinusoidal applied voltage was 115 V, and the output voltage was 70 V. The voltage across the inductance was thus some 50 % of E and approximately equal to V.

Table 3

$\delta V/E$	0	0·05	0·1	0·2	0·3	0·5	0·7
A/I	1·41	1·39	1·37	1·35	1·35	1·32	1·2
Power factor	0	0·42	0·5	0·6	0·69	0·79	0·81

The distortion of the wave-form applied to the rectifier was thus very great. Yet at this load the presence of the inductance caused the output current to fall by 8·2 %, from 4·25 mA to 3·9 mA. When the load resistance was varied it was found that the inductance increased the voltage-drop by an amount which was proportional to $\delta V/E$, reaching 10 % when $V/E = 50$ %.

From this experiment it would seem that the leakage inductance of an ordinary transformer cannot cause an appreciable drop of output voltage. The relative magnitude of the inductance used in the experiment just described, and the leakage inductance of a normal transformer, may be assessed as follows.

Let the leakage reactance drop at rated full-load current I_F be 5 % of the output voltage, so that

$$pLI_F = \frac{E}{20\sqrt{2}}$$

Then, reckoning that I_F must be, say, $2 \cdot 5I$, it follows that $pLI = E/71$. In the experiment described, $pLI = 20$ volts and thus $pLI = E/5 \cdot 8$. Thus it would seem that the inductance causing the distortion depicted by Fig. 9 is about 12 times as great as that associated with a normal transformer. Experiment showed that the presence of an inductance one-sixth the value of that used for delineating Fig. 9 caused no measurable change of output current at any value of V/E.

Since $v = L \,.\, di/dt$, it follows that the voltage curve of Fig. 9 is proportional to the slope of the current pulse. The voltage rises comparatively slowly to its negative maximum because of the curvature of the foot of the diode characteristic. It falls much more quickly from its positive maximum, because consideration of Fig. 9 will show that the resultant voltage across the rectifier must necessarily fall at a very great rate near the point where conduction ceases. Consideration will show that the inductance causes conduction to cease

later in the cycle than it would otherwise do: this is illustrated by Fig. 9, in which are shown the current curves both with and without series inductance. Lengthening the conduction period tends to increase the area of the current pulse and thereby tends to compensate for the reduction of area which otherwise would occur.

It will now be shown that the internal resistance of the transformer is competent to produce a very considerable voltage-drop in a rectifier which is working at an efficiency round about 90 %. Let the internal resistance of the transformer be r' and suppose that

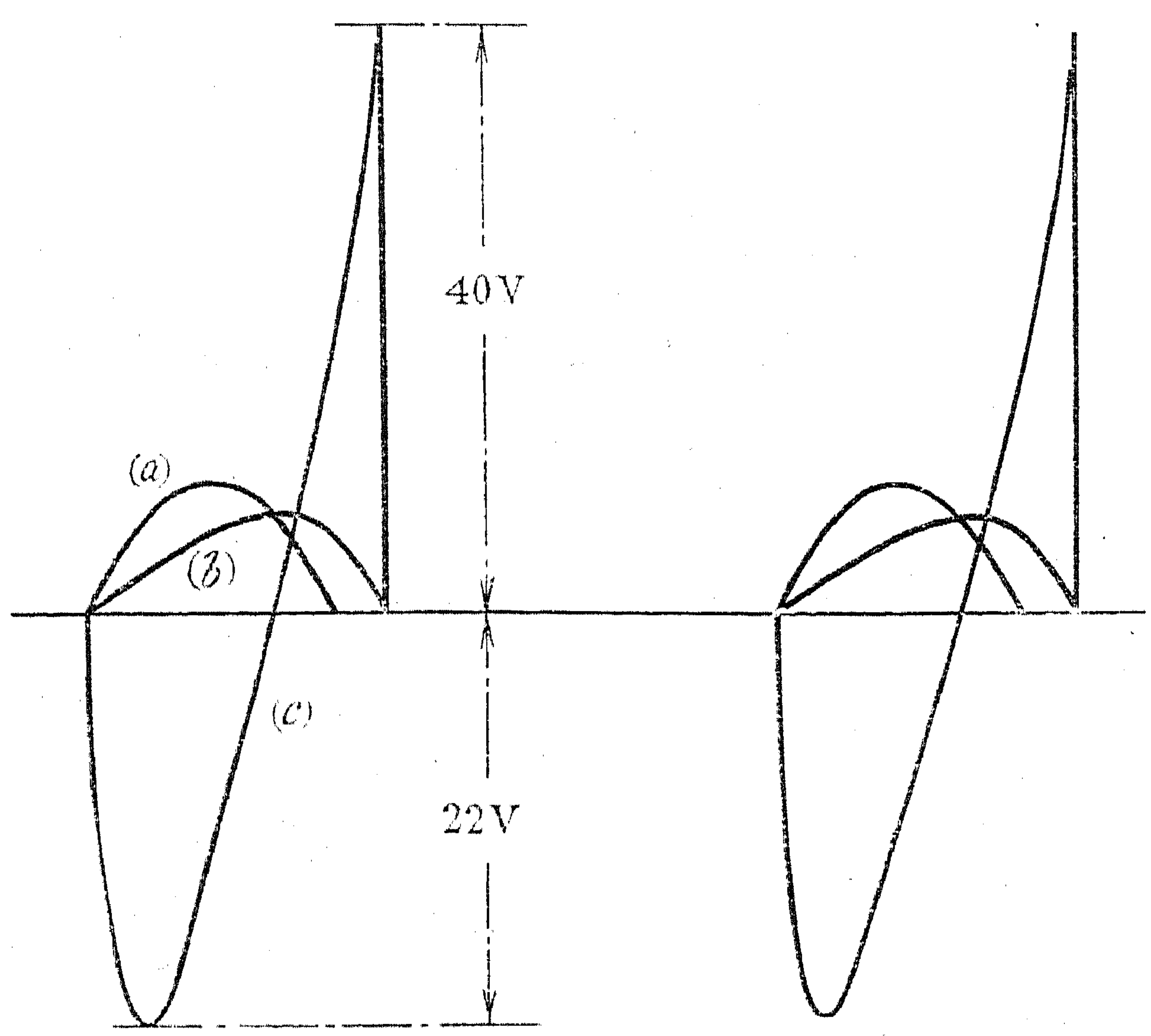

Fig. 9

(*a*) Current pulse without series inductance.
(*b*) Current pulse with series inductance.
(*c*) P.d. across 5 000-ohm inductive reactance, $V = 80$; $E = 112$; $I = 4 \cdot 1$ mA; $pL = 5\,000\ \Omega$.

$r'I_F$ is equal to, say, $E/100$. Hence, taking $I_F = 2 \cdot 5I$, it follows that

$$r' = \frac{E}{250I}$$

$$= \frac{3 \cdot 34}{250}\rho\left(\frac{E}{\delta V}\right)^{3/2}$$

Therefore

$$\frac{r'}{\rho} = \frac{1}{75}\left(\frac{E}{\delta V}\right)^{3/2}$$

$$= 0 \cdot 15 \text{ if } \frac{E}{\delta V} = \frac{10}{8}$$

If $\frac{\delta V}{E} = 0 \cdot 9$, then $I_F = 3I$, and $\frac{r'}{\rho} = 0 \cdot 35$.

The effect of r' on the mean output voltage will be to increase ρ in the ratio $(\rho + r')/\rho$, and hence for a given current to increase $\delta V/E$ in the ratio $[(\rho + r')/\rho]^{2/3}$. Thus if $r'/\rho = 0 \cdot 35$, the voltage-drop will be 22 per cent greater than it would have been if r' were zero.

The resistance of the transformer should cause an oscillogram of the output voltage from the transformer to show a curve symmetrical about its mid-ordinate, but having a top much flatter than a sine curve: the leakage inductance will cause dissymmetry.

(9) DISPOSITIONS USING MORE THAN ONE RECTIFIER

(a) Centre-Tap-Transformer Method.

One such arrangement is shown in Fig. 10 and is often called "full-wave" rectification. Here two valves are connected in series, and the load resistance, with its reservoir condenser, is connected between the junction point of the two cathodes and the middle point of the output winding of the transformer. A familiar variation employs one cathode and two anodes within a common envelope.

The load circuit now receives a pulse of charge every half-cycle, and hence, in the notation of Section (3), $A = I/(\pi\rho)$ instead of $I/(2\pi\rho)$ for a "half-wave" system. Thus equation (6*a*) is applicable, provided that ρ be replaced by the joint resistance of the two diodes in parallel, and the symbol E refers to the peak voltage

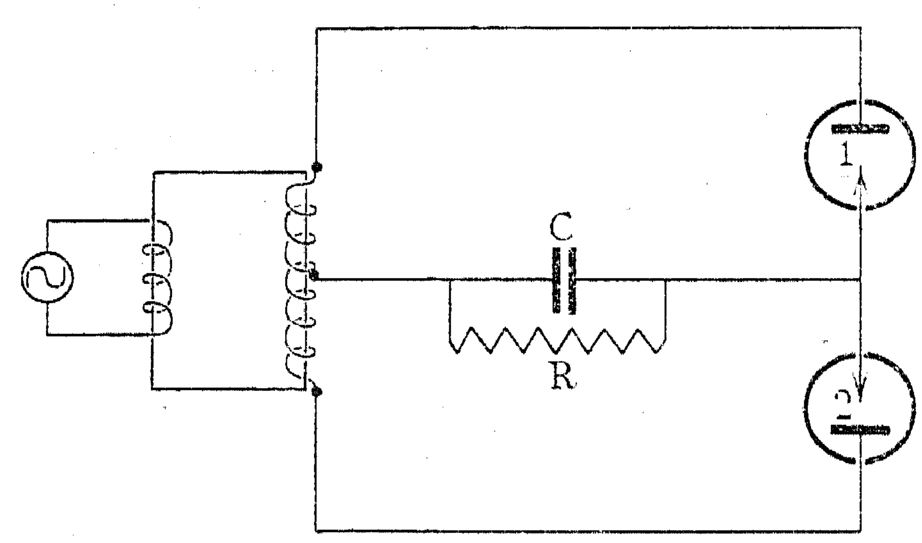

Fig. 10

between the centre tap and one output terminal of the transformer. Valve 1 is conducting during a portion of one half-cycle of applied voltage, and valve 2 during the corresponding portion of the succeeding half-cycle, and thus at any given instant there is never current flowing in both halves of the output winding. Hence equation (14) for I_2 remains unaltered, provided that I be replaced by $\frac{1}{2}I$: thus for a full-wave rectifier the values of I_2/I shown in Table 2 must be divided by 2. For a given value of C, the ripple from a full-wave rectifier will be half that from a half-wave rectifier. Provided such obvious adjustments are borne in mind, the whole of the analysis of this paper may be applied to the full-wave arrangement.

(b) Centre-Tap-Capacitance Method.

The circuit diagram of this arrangement is shown in Fig. 11. The connection MM′, shown dotted, is not essential and is seldom used. It is included here because it makes more obvious the similarity between Fig. 11 and Fig. 1. If this connection is included, the arrangement may be regarded as two separate rectifiers and loads fed from one transformer, the valves being connected so that conduction occurs in one or other of them during a portion of each half-cycle of applied voltage. In the previous notation, the mean voltage across each condenser is V, and consequently across the whole load $2R$ it is $2V$. So long as the impedance of C is small compared with $2R$, removing the connection MM′ will produce no effect. Consequently the analysis appropriate to the circuit of Fig. 1 is also appropriate to that of Fig. 11 with the dotted connection MM′

removed—so long as it is remembered that δV in equation (6) *et seq.* is to be taken as half the difference between $2E$ and the output p.d. It appears that for equal values of C and R the fractional value of the ripple will be the same for Fig. 11 as for Fig. 1. The load output in Fig. 11 is, however, twice that in Fig. 1, and consequently the mean square current in the output winding of the transformer is also doubled. Consequently the value of the ratio I_2/I collected in Table 2 must be doubled, while remembering that δV in this table must be reckoned as half the difference between $2E$ and the output voltage.

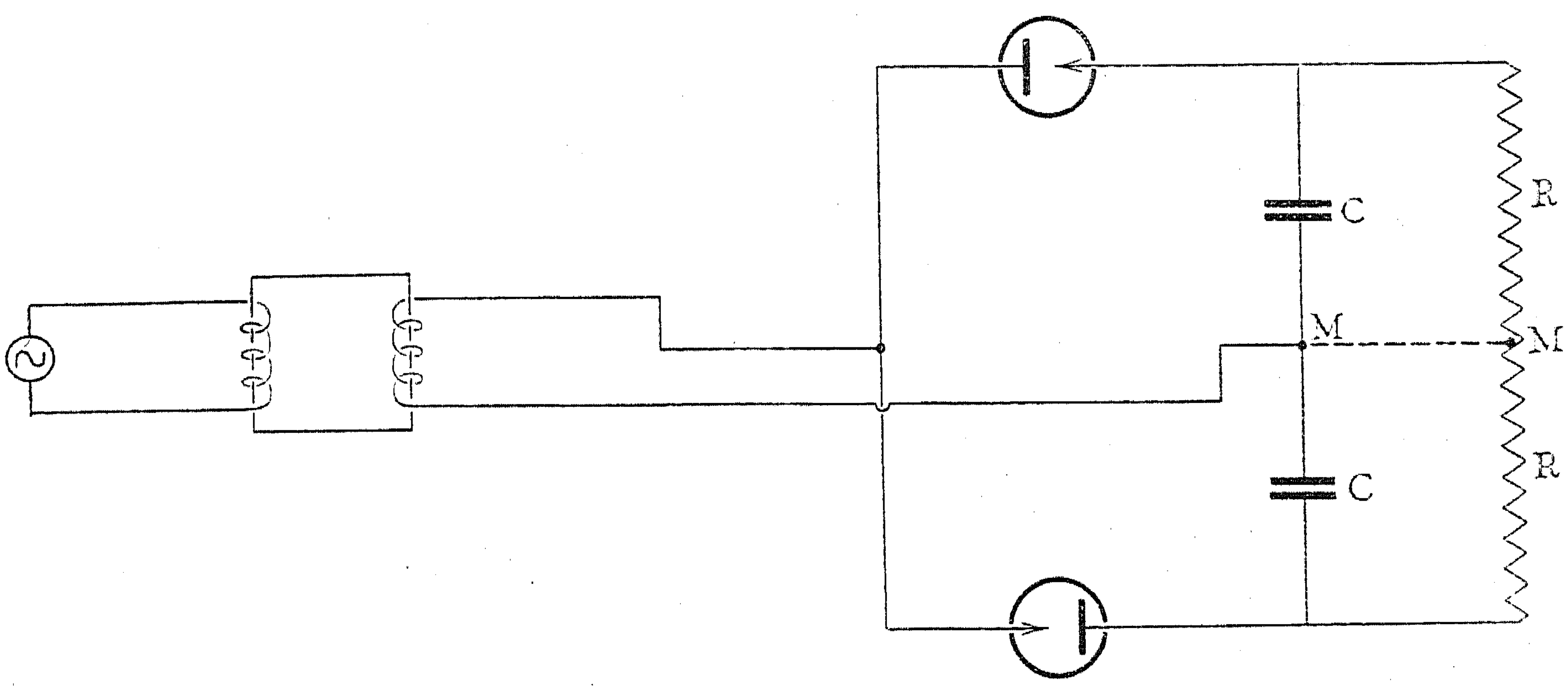

Fig. 11

(c) Cascade Connection of Rectifiers.

This system, associated with the name of Mr. J. D. Cockcroft,* is used when it is required to produce an output voltage much greater than the voltage of the alternating-current supply. The circuit diagram for a two-stage Cockcroft rectifier is shown in Fig. 12.

If valve 2 were disconnected, then the potential of the point A would fluctuate between $2E$ and zero, the capacitance C_1 being charged to a p.d. E. If valve 2 be now connected to the point A and the load R be absent, then capacitance C_2 would become charged to a p.d. $2E$. If the load R be now connected across C_2, power will be delivered to it at a p.d. approximating to $2E$. When valve 2 becomes conducting, current will flow from the source to the load through it and C_1. If C_1 is very large, the p.d. across valve 2 during the conducting epoch will differ insensibly from the cap of a sine curve, such as is shown shaded in Fig. 3, and consequently the quantity of electricity which flows through valve 2 will be equal to A/ρ in the previous notation. When a steady state has been reached an equal quantity must flow into C_1 during the succeeding half-cycle of applied voltage. Hence if the mean p.d. across C_1 be V, then that across C_2 will be $2V$ and the relation between $2V$ and I will be

$$\left(\frac{2E-2V}{2E}\right)^{3/2} \simeq 3\cdot 34\frac{\rho I}{E} \quad . \quad . \quad . \quad (6b)$$

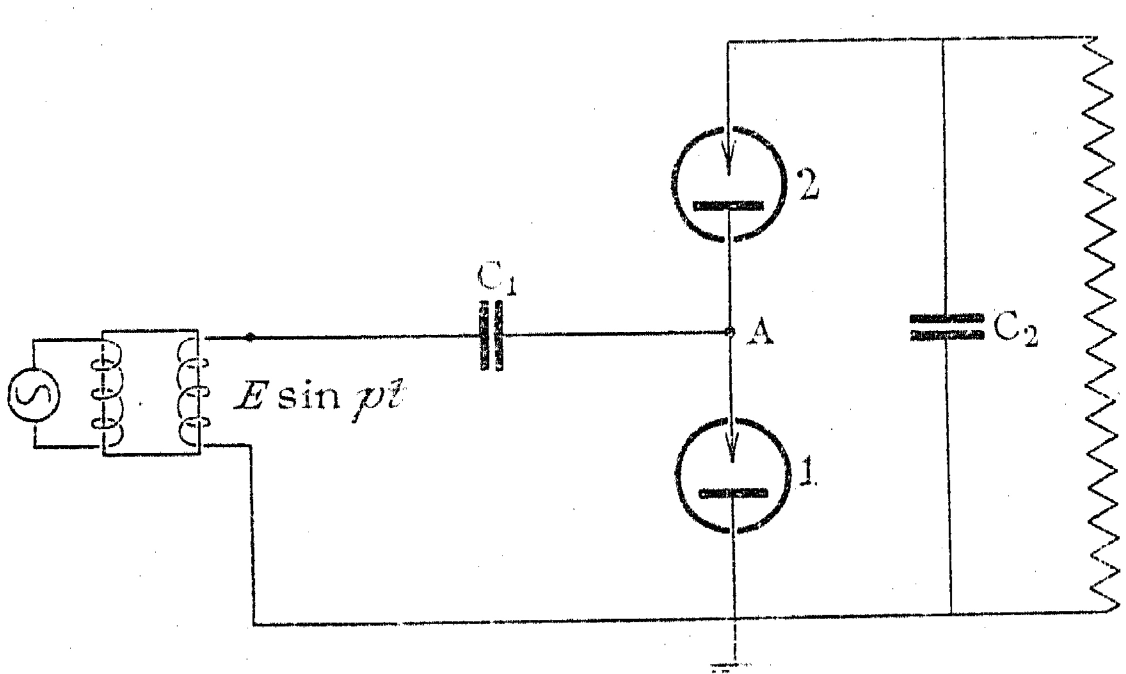

Fig. 12

Since C_2 receives a pulse of charge every alternate half-cycle, the fractional amplitude of the voltage ripple will depend only on C_2 and R. Hence the output of the arrangement of Fig. 12 is indistinguishable from that of Fig. 11, and likewise from that of Fig. 1, provided that the input voltage to Fig. 1 be raised from $E \sin pt$ to $2E \sin pt$.

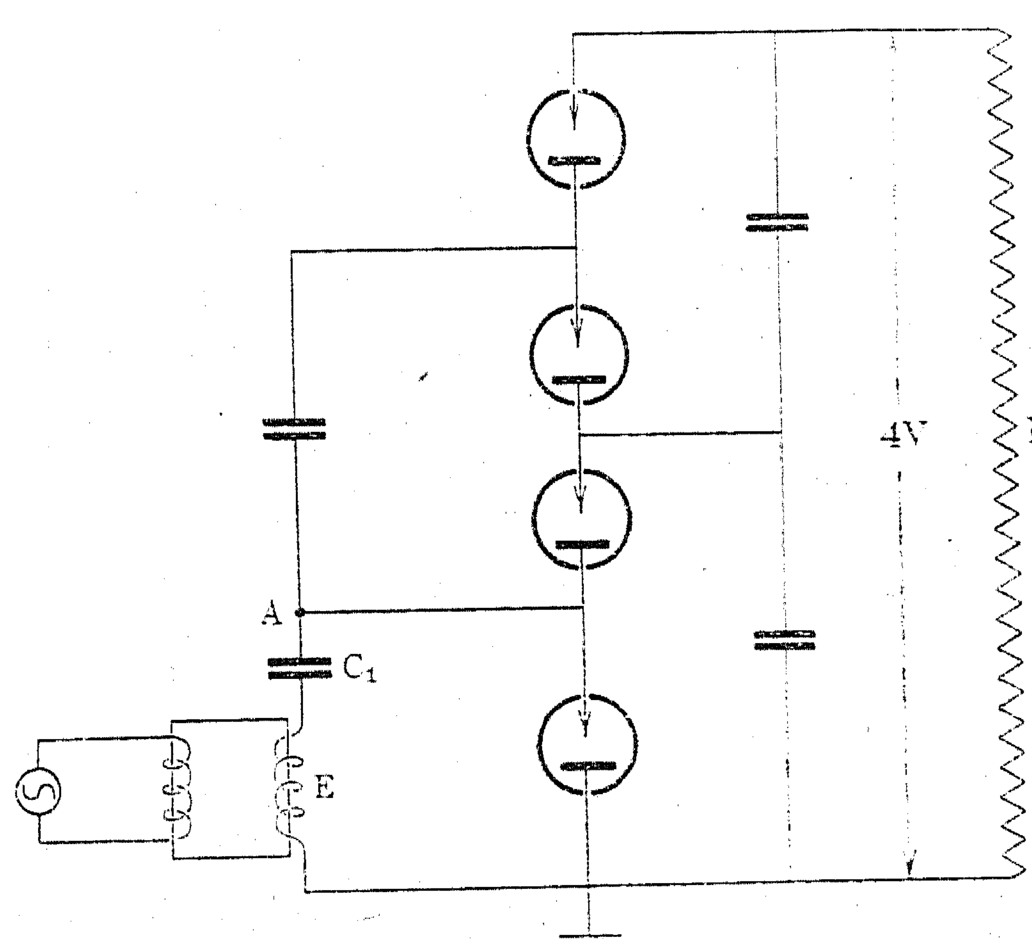

Fig. 13

The cascade arrangement of Fig. 12 can be extended indefinitely, a four-stage system being shown in Fig. 13. The relation between output current and voltage will

* See *Proceedings of the Royal Society*, A, 1932, vol. 136, p. 619.

still be given by equation (6*b*), if $4E$ and $4V$ are substituted for $2E$ and $2V$. But it must be remembered that, for a given output current, the condenser C_1 of Fig. 13 must take in and give out each half-cycle twice the quantity of electricity taken in or given out by condenser C_1 in Fig. 12. It thus seems possible that the output p.d. of a cascade Cockcroft rectifier may be more sensitive to the size of the reservoir condensers than is the output p.d. of a single-valve circuit.

(10) RECTIFIER USED FOR TRICKLE CHARGING OF ACCUMULATORS

The analysis of Section (3) is unaltered if the load resistance and reservoir condenser of Fig. 1 are replaced by an accumulator battery of voltage V_B, and hence the relation between mean charging current I and battery voltage V_B is seen to be

$$\left(\frac{E - V_B}{E}\right)^{3/2} = 3\cdot 34\frac{\rho I}{E}$$

Thus, for example, the characteristic shown in Fig. 7 might be replotted so as to show current as ordinates and number of cells as abscissae. Thus, suppose 40 cells were to be charged through this tube from an a.c. supply of 100 volts r.m.s. At the commencement of the charge the battery p.d. would be 80 V and the charging current would be 8·5 mA. At completion of charge the battery p.d. would be nearly 104 V and the charging current would have fallen to 3·5 mA.

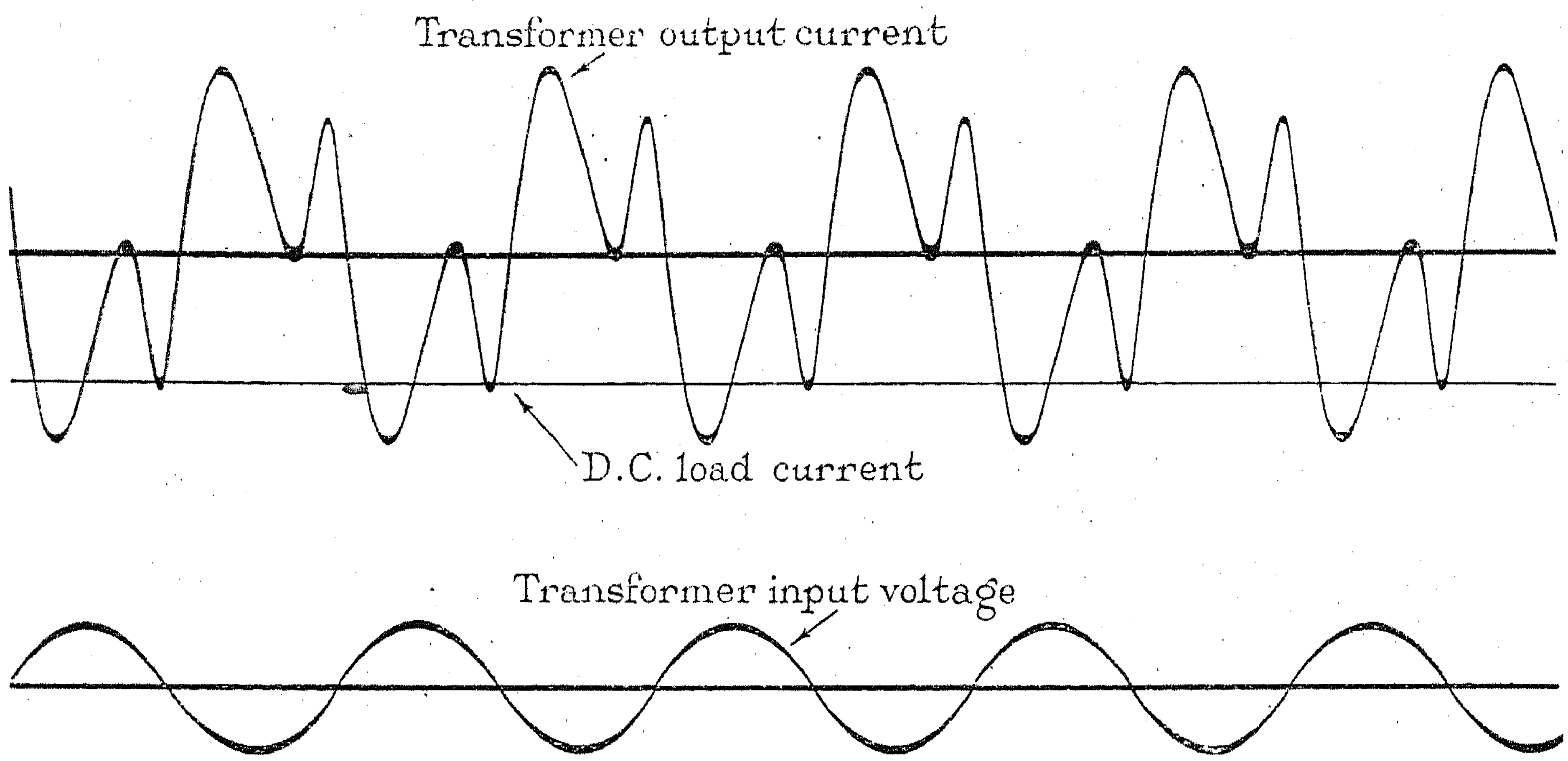

Fig. 14

ACKNOWLEDGMENT

The author wishes to thank Prof. B. L. Goodlet, lately of the Research Department of Messrs. Metropolitan-Vickers Electrical Co., Ltd., for the interest he has taken in this problem, for valuable criticisms of the manuscript, and for suggesting some of the experimental work, which was carried out in the Engineering Laboratory of Oxford University; also to thank Mr. A. W. G. Birch and Mr. F. R. Franks for helping him with some of the experimental work.

APPENDIX

Since the manuscript of this paper was submitted to The Institution, an analysis of this problem has been published by Mr. N. H. Roberts.* Mr. Roberts's work is concerned largely with the relation of V/E to the size of the reservoir condenser. This effect has been ignored in the present paper because it was argued (see Section 4) that it was inappreciable until the size of the condenser was such as to make the fractional ripple in the voltage intolerably large. In Figs. 12, 13, and 14, of Mr. Roberts's paper, V/E is plotted as a function of $m = pRC$ for various values of the ratio $n = \rho/R$.

If C is absent, then it can readily be shown that

$$\frac{V}{E} = \frac{1}{\pi} \times \frac{1}{(1+n)}$$

Hence the limiting values of V/E for m zero and for m infinite are known. It follows from equation (1) of the present paper that Z, the fractional ripple, is related to m by the equation $m = 2/(\pi Z)$: thus, when $m = 25$, $Z = 25\ \%$. Mr. Roberts's curve (Fig. 13) shows that if V/E is 0·95 with C infinite ($n = 1/400$), then V/E is 0·9 when $m = 25$. Thus his solution endorses the rather arbitrary statement in Section (4) of the present paper, "that the output voltage is sensibly independent of the size of the reservoir condenser, provided this is such as to make the ripple less than, say, 20 %". For larger values of n, a finite value of C has even less effect: this follows because the extreme possible reduction of V becomes relatively smaller as n increases. Thus if $n = 1/4\cdot 7$, then V/E is 0·5 with C infinite and 0·26 with C zero; whereas with $n = 1/400$, V/E can have any value between 0·95 and $\frac{1}{\pi} \times \frac{400}{401} = 0\cdot 316$, according to the value of m. Curve 12 of Mr. Roberts's paper is a similar curve for the "full-wave" rectifier. In this the limiting lower value of V/E is $\frac{2}{\pi} \times \frac{1}{n+1}$, and hence it follows that V is even less dependent on C than it is in a half-wave rectifier. His curve (Fig. 14) for the "voltage doubler" or "centre-tap capacitance"

* See *Wireless Engineer*, 1936, vol. 13, pp. 351 and 423.

rectifier, shows that if $V/E = 0\cdot95$ when C is infinite, then $V/E = 0\cdot82$ when $m = 25$. In this method of connection V must depend more on C than it does in a "half-wave" rectifier, since in this the lower limit of V is zero. His curve shows that if m is not less than 25, then V is independent of C to an accuracy closer than 5 %, so long as V/E is not greater than $0\cdot85$. In short, the simplification obtained by disregarding the value of C is fully justified so long as C is large enough to cause the ripple to be not greater than about 20 %.

Figs. 8–10 of Mr. Roberts's paper exhibit I_2/I as a function of m. They show that this quantity is sensibly independent of C so long as m is greater than 25 and so long as $\delta V/E$ is greater than about 5 %. The limiting values (with m infinite) of I_2/I shown in Mr. Roberts's curve (Fig. 9) agree with those shown in Table 2 of the present paper. His curve (Fig. 8) for the "full wave" rectifier shows I_2/I as measured in the lead to the centre tap of the transformer: his limiting values are thus $1/\sqrt{2}$ of those collected in Table 2. He does not arrive at an explicit relation, corresponding to equation (6*a*) of this paper, between V and I, but the curve relating these two quantities could be deduced from his Fig. 13.

Mr. W. H. Aldous* has analysed the behaviour of a rectifier in which the diode characteristic is $i = kv^{3/2}$ and obtains the relation

$$\left(\frac{\delta V}{E}\right)^2 = \frac{3\cdot75I}{kE^{3/2}}$$

Writing $\dfrac{\delta V}{I_{max}} \equiv \rho$ this takes the form

$$\left(\frac{\delta V}{E}\right)^{3/2} = \frac{3\cdot75\rho I}{E}$$

which is now in the same form as

$$\left(\frac{\delta V}{E}\right)^{3/2} = 3\cdot34\frac{\rho I}{E} \quad . \quad . \quad . \quad . \quad (6a)$$

Thus for a given value of $(\delta V/E)$ the 3/2-power law of the diode characteristic will result in the current being $10\cdot1$ % less than it would have been if the diode characteristic had been a straight line.

The author is indebted to the research department of Messrs. Metropolitan-Vickers Electrical Co., Ltd., for the oscillogram reproduced in Fig. 14. This shows the output current of the transformer and the d.c. load current from a 4-stage "Cockcroft circuit" giving a d.c. output of 5 mA at approximately 400 kV.

* *Wireless Engineer*, 1936, vol. 13, p. 576.

DISCUSSION ON "FLUCTUATION NOISE IN VACUUM TUBES WHICH ARE NOT TEMPERATURE-LIMITED"*

Mr. G. L. Pearson (U.S.A.) (*communicated*): The paper by Dr. Williams reports the measurements of noise in diode vacuum tubes operated so that the anode current is limited by space charge. The results are in good agreement with those previously reported by me† and, in addition, extend the range of the earlier measurements to much higher space currents. The difference between this paper and mine lies in the explanation of the experimental results. My data support the view of Llewellyn‡ that at complete space charge the shot voltage is zero, and that the remaining noise is equivalent to a thermal agitation of the electric charge in the internal plate resistance of the vacuum tube and in the external load resistance, the theoretical equation for which is

$$\overline{E^2} = 4kT_0R\left(1 + \frac{T_fR}{T_0R_p}\right)\left(\frac{R_p}{R + R_p}\right)^2 df \quad . \quad (A)$$

where $\overline{E^2}$ is the mean-square noise voltage, k is Boltzmann's gas constant, T_0 and T_f are respectively the room and filament temperatures in degrees Kelvin, R_p is the internal plate resistance of the vacuum tube, R is the load resistance, and df is the frequency range of the associated amplifier.

On the other hand, Dr. Williams uses his experimental data to support Moullin and Ellis§ in their view that there is no thermal agitation voltage inside the tube and that the noise at complete space charge is a residual shot effect which, combined with the thermal noise in the load resistor, is

$$\overline{E^2} = (4kT_0R + 2eIR^2)\left(\frac{R_p}{R + R_p}\right)^2 df \quad . \quad . \quad (B)$$

where e is the electronic charge, and I the mean value of the anode current.

In the region of retarding anode potentials where the logarithm of the space current is proportional to the anode potential, Dr. Williams shows that equations (A) and (B) are identical if T_f in equation (A) is replaced by $\frac{1}{2}T_f$. Since my experimental results checked equation (A) when the same substitution was made, he suggests that my tubes must have been working on the exponential portion. This was not the case, however, as is shown in Fig. A, in which $\log I$ is plotted against plate potential for my oxide-coated tube No. 1. The initial portion is a straight line, but this bends to the right at about 0·5 volt and is concave downward over the entire working range of the previous paper, which was between 10 and 200 microamperes space current, or 3 600 and 15 700 ohms plate impedance.

* Paper by Dr. F. C. Williams (see vol. 78, p. 326).
† "Shot Effect and Thermal Agitation in a Space Charge Limited Current," *Physics*, 1935, vol. 6, p. 6.
‡ "A Study of Noise in Vacuum Tubes and Attached Circuits," *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 243.
§ "The Spontaneous Background Noise in Amplifiers due to Thermal Agitation and Shot Effects," *Journal I.E.E.*, 1934, vol. 74, p. 323.

I have made additional noise measurements on oxide-coated tube No. 1, using a circuit identical with that previously described, and I have obtained data at lower plate resistances (higher plate currents) as well as over the range already covered. These data are plotted as experimental points in Fig. B, where ordinates represent mean-square noise voltage and abscissae the resistance

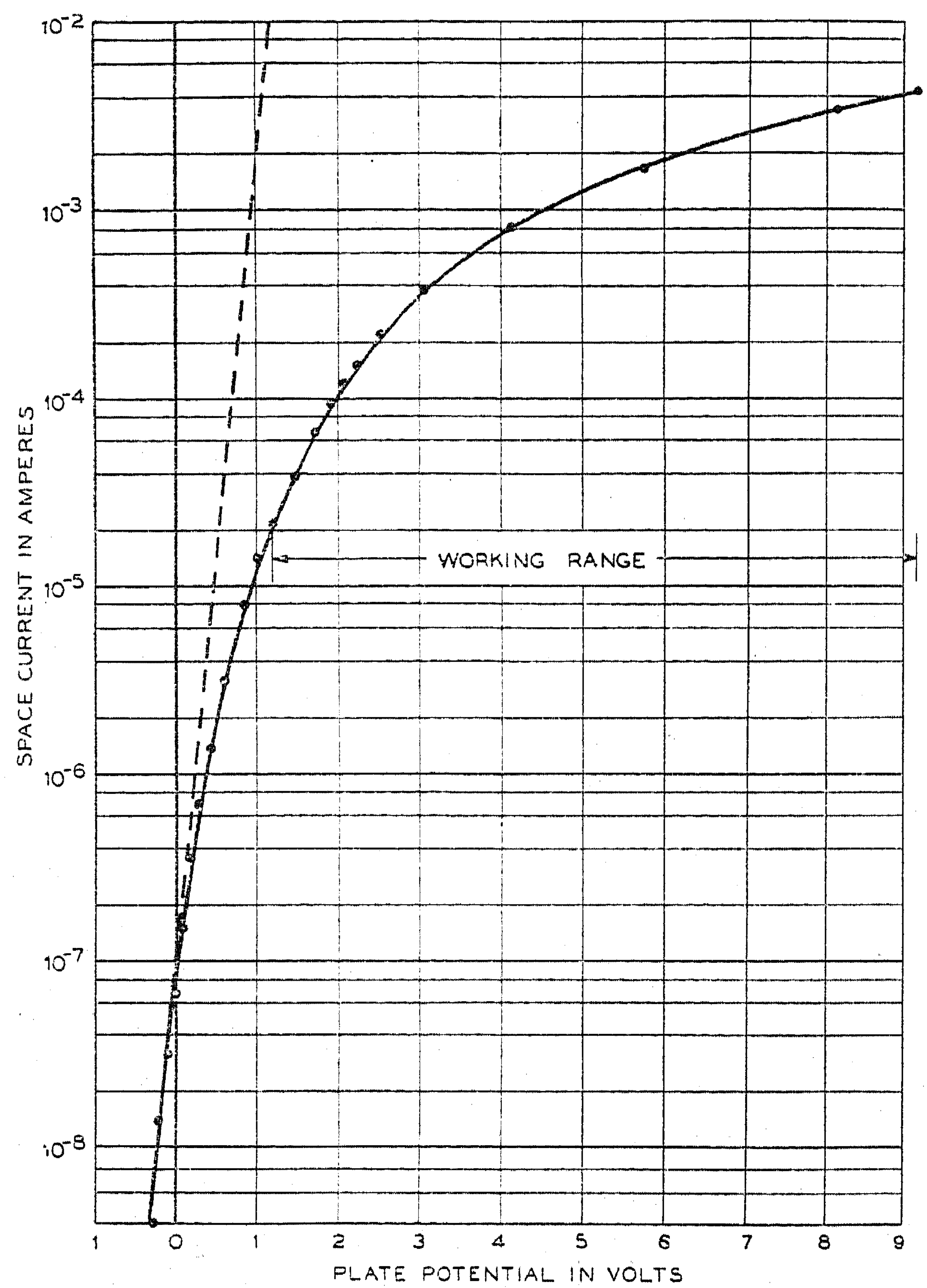

Fig. A.—Space current in amperes versus the plate potential in volts, for oxide-coated tube No. 1. The range over which noise measurements were taken is indicated.

of the load and the tube in parallel. Over the range previously reported, the results are identical, and at decreased plate resistance the noise reaches a minimum and then shows an increase as did the results of Dr. Williams.

The two solid lines in Fig. B give the noise as calculated by equations (A) and (B). [T_f in equation (A) has been given the value 650° K. rather than the temperature of the filament, which was approximately 1 100° K.] Whereas the experimental data are in complete agree-

ment with equation (A) at higher plate resistances and depart somewhat from it at the lower values, the noise calculated from equation (B) is too large over the entire range and is greater than the measured noise by a factor of 13 at the lower plate resistances.

The fact that T_f in equation (A) must be taken at 650° rather than 1 100° K., which is the actual temperature of the filament, has led Llewellyn to investigate again the effect of cathode temperature. Starting from general equations for the motions of electrons in vacuum tubes with varying degrees of space charge, he has derived a general equation for noise. For complete space charge this equation is identical with equation (A) except that T_f must be taken at 0·55 times the actual cathode temperature, in agreement with the experimental results of both Dr. Williams and myself. An independent derivation* based on an altogether different approach and involving a graphical integration reaches

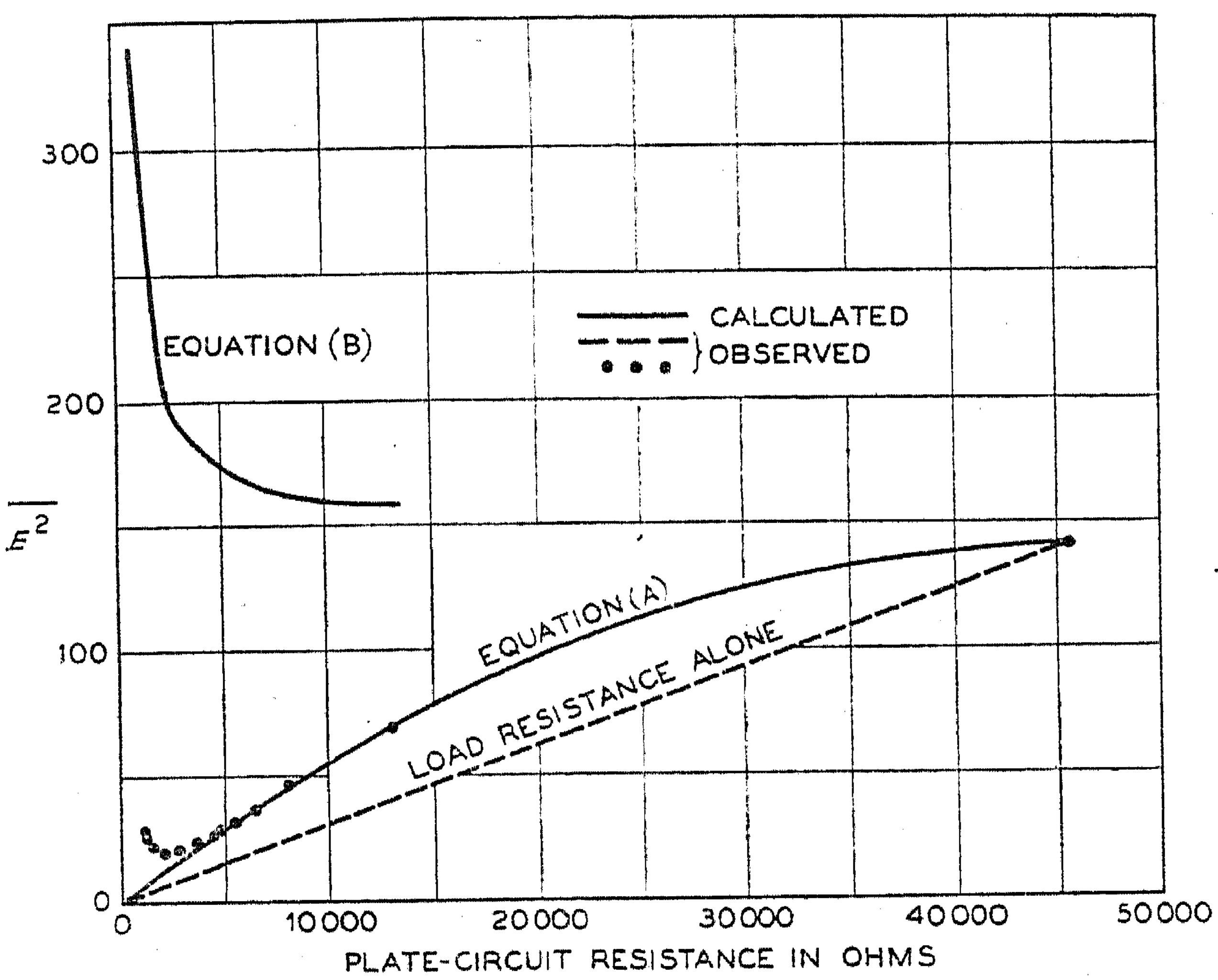

Fig. B.—Thermal noise in the plate circuit of oxide-coated tube No. 1.

The thermal noise in the load resistance when the vacuum tube is disconnected is represented by the broken line.
The experimentally measured values are represented by dots.
The full-line curves were calculated by means of equations (A) and (B).

substantially the same conclusion with a value of about 0·6 instead of 0·55.

The increase in noise at low internal plate resistances found by Dr. Williams and shown in Fig. 3 of his paper must be due to the fact that with increased anode current the space charge is no longer complete and some shot noise therefore appears. This explanation is verified in a second paper by Dr. Williams† which shows that the location of the noise minimum is dependent on the cathode temperature. The lower this temperature, the sooner is the noise minimum reached as the internal plate resistance is decreased (anode current increased) by raising the plate voltage.

The fact that Dr. Williams's noise data are dependent upon the frequency range also indicates that the space charge in his tubes is not complete and that, in addition to shot and thermal noise, he is measuring flicker effect, which, of course, is not included in either equation (A) or (B). Since the flicker effect decreases with an increase in frequency, the data obtained by Dr. Williams in the highest frequency range include less extraneous noise.

Although our experimental data cannot verify Llewellyn's theory over an extended range because of the lack of complete space charge at high space currents, they certainly show that Moullin and Ellis's equation cannot be correct, since over the entire range it predicts a noise larger than that measured.

Dr. F. C. Williams (*in reply*): I am interested to hear that Mr. Pearson's results were not obtained under a retarding field. It appears, however, that those points which support equation (A) were situated in the early part of the space-charge-limited range adjacent to the retarding field regime. In the space-charge region proper his results confirm mine, in that they show fluctuations greater than those predicted from equation (A).

It may be noted that my paper did not attempt to support equation (B) quantitatively; it was already known to overestimate the fluctuations. This is stated in the conclusion: "It may be possible to arrive at a correction factor having a rational basis, which will allow the Schottky form (typified by B) to be used in all circumstances and without resort to a thermal-agitation interpretation of a part of the effect."

The second paper was devoted to an experimental investigation of the required correction factor, A.

Mr. Pearson suggests that my tubes were not completely space-charge-limited, and that flicker effect obscured the investigation. His inference is based on the behaviour of $A_{min.}$* $A_{min.}$ occurs at high space currents corresponding to the transition from space charge to temperature limitation. High currents also give increased flicker effect. The curves, however, cover a wide current-range, 10^{-3} to 10 mA, and behaviour at high currents is an unsound test of the degree of space charge at lower currents. In fact, the inference to be drawn from these curves is, that space charge is complete for all currents appreciably less than that corresponding to $A_{min.}$ It can similarly be inferred that flicker effect makes a minor contribution below $A_{min.}$

This problem of ensuring complete space charge and freedom from flicker effect and other extraneous effects is, of course, one of the major difficulties of fluctuation investigations. On this account comprehensive data were obtained relating to the effect of temperature and frequency response. Sufficient of this data is included in the quoted figures to show that the required conditions were sufficiently satisfied over a wide range of currents yielding results at variance with equation (A).

It does not therefore seem possible to accept Mr. Pearson's explanation of the observed discrepancies in terms of flicker effect and incomplete space charge. The discrepancies are not at once apparent from Figs. 3, 8, and 9. Fig. 5 shows the results of Fig. 3 in a different form, in which the discrepancies are at once apparent. Further evidence can be deduced as follows: If, in accordance with Mr. Pearson's suggestion, we suppose that failure of experiment to support equation (A) is due

* B. J. Thompson and D. O. North: oral presentation at Rochester meeting of Institute of Radio Engineers, 16 Nov., 1936, and abstracted in *Electronics*, 1936, vol. 9, p. 31. In the discussion of this paper Llewellyn described his derivation.
† "Fluctuation Voltage in Diodes and in Multi-Electrode Valves," *Journal I.E.E.*, 1936, vol. 79, p. 349.

* Figs. 3, 4, 8, and 9, *Journal I.E.E.*, 1936, vol. 79, pp. 353 and 356.

to the coexistence of thermal agitation and shot effect owing to incomplete space charge, the noise generated in the tube, exclusive of that produced by thermal agitation in the load resistance, would be

$$\bar{v}^2 = \left(2I_1 e + \frac{4kT_f}{R_p}\right)\left(\frac{RR_p}{R+R_p}\right)^2 df \quad . \quad . \quad (C)$$

where I_1 is that temperature-limited current which yields a fluctuation equal to the shot component. My paper expresses the fluctuations entirely as shot effect, by means of the equation

$$\bar{v}^2 = 2IAe\left(\frac{RR_p}{R+R_p}\right)^2 df \quad . \quad . \quad . \quad (D)$$

where I is the anode current and A is a correcting function whose value is determined by experiment. Referring the above equations to the same set of results, we have

$$A = \left(\frac{I_1}{I} + \frac{2k}{Ie} \cdot \frac{T_f}{R_p}\right) \quad . \quad . \quad . \quad . \quad (E)$$

Experiment showed* that, with a given current, A was not vastly dependent on R_p, two values of R_p being obtained for each current value by connecting the grid, (*a*) to the anode, and (*b*) to the cathode. In Fig. 3 a 5 : 1 change of R_p gave about 25 % mean change of A. In Fig. 8 a 40 : 1 change of R_p gave 33 % change of A. In Fig. 9 the figures were 14 : 1 and 30 %. These figures refer to the linear branches of the curves where space charge is believed to be complete. It follows that the second term in equation (E) is negligible compared with the first, even with the low values of R_p (grid to anode). The total noise, with grid to anode, corresponding to these values of A was never vastly greater than that expected from thermal agitation with full cathode temperature. Hence the conclusion ". . . thermal agitation in the anode stream is either non-existent or negligible."†

From the technological viewpoint there can be no doubt that the "shot" interpretation is the better, for the second paper shows that fluctuations in pentodes can then be satisfactorily explained in terms of the fluctuations in the same valve used as a diode. That is, A is not vastly dependent on the subdivision of cathode current or the configuration of collecting electrodes. In pentodes R_p is several thousand times greater than in a diode with equal cathode current, thus supplying further proof that the second term in equation (E) is negligible. Further, if the tube be used as a diode the fluctuations, expressed solely as thermal effects,* require a mean T_f about equal to the cathode temperature. Similar interpretation of the pentode results would require a value of T_f several thousand times greater than the cathode temperature.†

It may be argued that changing the electrode connections upsets the space-charge conditions, and that deductions based on such changes neither prove nor disprove equation (A). However, space charge is densest in the vicinity of the cathode where potential conditions are not vastly upset by changed electrode connections, provided the electrode potentials are readjusted to give an equal cathode current. Further, the second paper showed that such changed connections did not invalidate the shot interpretation.

It may also be noted that equation (A) has not been analytically restricted to diodes.‡ If it represents a true thermal agitation effect, it should hold equally well for triodes or pentodes, where experiment has shown it to to vastly in error. If, in fact, equation (A) is limited to diodes, then it has no technological value, and it appears probable that any agreement with equation (A) in diodes is due to a mechanism which is similar to that described in my first paper, and which makes shot and thermal expectations equal.

The derivations of the "0·55" and "0·6" laws mentioned by Mr. Pearson do not appear to have been published in full. It would be interesting to know whether these results refer to the retarding field as well as to the space-charge region.

* Figs. 3, 8, and 9.

† Summary to second paper (see *Journal I.E.E.*, 1936, vol. 79, p. 349).

* $I_1 = 0$ in equation (E).

† See also Fig. 5 in the second paper, showing a similar result for a triode.

‡ F. B. LLEWELLYN: *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 243.

AN EXPERIMENTAL INVESTIGATION OF THE THEORY OF EDDY CURRENTS IN LAMINATED CORES OF RECTANGULAR SECTION*

By M. REED, M.Sc.(Eng.), Associate Member.

(*Paper first received 4th August, and in final form 3rd December, 1936.*)

SUMMARY

It is shown that a complete verification of the well-known theory of eddy-current shielding in plane sheets can be obtained by measuring the variation of the impedance with frequency of a coil wound on a laminated core consisting of non-magnetic material.

The verification of the theory is straightforward when the screening effect is small, because laminations thin enough to simulate the conditions of the plane sheet can be used, whereas much thicker laminations are necessary when the screening effect is large, and the simple theory must be extended to include the ratio of lamination thickness to lamination width. This extension is derived from an analysis of the eddy currents in an elliptical core, which, as the measurements show, applies to a rectangular core when the screening effect is large.

When the screening effect is small, however, the results of the analysis of the elliptical core no longer apply to the rectangular one, and the difficulties of obtaining a mathematical solution in this case are indicated.

With magnetic laminations the simple theory no longer holds in practice, and Peterson and Wrathall have shown that it is necessary to modify this theory to take into account the presence of a surface layer. The modifications are examined in an Appendix, and the results obtained indicate that they apply when the screening effect is negligible but not when it is large. Nevertheless, the equations obtained by Peterson and Wrathall are shown to provide a means of evaluating the thickness of the surface layer.

LIST OF SYMBOLS

$p = \dfrac{8\pi a^2}{k\rho \times 10^9}$;

$m = 2\pi\sqrt{\left(\dfrac{\mu f}{\rho \times 10^9}\right)}$;

$k = \dfrac{4\pi N^2 A}{l} \times 10^{-9}$;

$2a$ = thickness of lamination, in cm.;

$2b$ = width of lamination, in cm.;

ρ = resistivity of core, in ohms per cm. cube;

μ = permeability of core;

f = frequency, in cycles per sec.;

N = number of turns in coil winding;

A = area of core cross-section, in cm.^{2};

l = mean circumference of core, in cm.;

R_e = resistance of the coil due to the presence of the core;

L_e = inductance of the coil due to the presence of the core.

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INTRODUCTION

Since the formulation of the theory of eddy-current shielding in plane sheets by J. J. Thomson† many years ago, a number of investigators have attempted to verify this theory using magnetic materials for their measurements. Although general agreement with the theory has been established so far as the variation of the measured quantities with frequency is concerned, the investigators have all found discrepancies between the measured and calculated values. Alexanderson‡ thought that the differences were due to the fact that the coils on which the measurements were made had incomplete magnetic paths, whereas Wilson§ found that they still existed when the magnetic paths were complete. Jouast|| postulated the inclusion of a dielectric constant in the theory to account for his results, and McLachlan¶ thought that the discrepancies could be explained by the variation of permeability throughout the thickness of each lamination. Jordan** and Scott†† believed that, in addition to the normal eddy-current and hysteresis losses, a loss arising from some form of molecular lag or viscosity would account for their results. A recent paper‡‡ by Peterson and Wrathall indicates, however, that the discrepancies obtained with magnetic materials arise from the fact that, in practice, such materials are rarely homogeneous, the inhomogeneity taking the form of a thin surface layer which has a permeability much less than that of the interior, and that these discrepancies practically disappear with the removal of the surface layer.

From the foregoing it is clear that, whatever the reason, the use of magnetic materials introduces considerable complications in the attempt to verify the eddy-current theory of shielding. To avoid these difficulties it was decided to make the necessary measurements on coils whose cores were built up of non-magnetic laminations.

EQUATIONS FOR THE PLANE SHEET

It is convenient to investigate the shielding effects of eddy currents by measuring the impedance of a coil wound on a core of the material under consideration. Scott§§ has shown that the resistance and inductance of

† J. J. THOMSON: *Electrician*, 1892, vol. 28, p. 599.
‡ E. F. W. ALEXANDERSON: *Transactions of the American I.E.E.*, 1911, vol. 30, p. 2433.
§ L. T. WILSON: *Proceedings of the Institute of Radio Engineers*, 1921, vol. 9, p. 56.
|| R. JOUAST: *La Lumière Electrique*, 1916, vol. 32, pp. 207, 236.
¶ N. W. MCLACHLAN: *Journal I.E.E.*, 1916, vol. 54, p. 480.
** H. JORDAN: *Elektrische Nachrichten-Technik*, 1924, vol. 1, p. 7.
†† K. L. SCOTT: *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 1750.
‡‡ E. PETERSON and L. R. WRATHALL: *Proceedings of the Institute of Radio Engineers*, 1936, vol. 24, p. 275.
§§ *Loc. cit.*

such a coil due to the presence of the core material alone are given respectively by equations (1) and (2), namely

$$\frac{R_e}{2\pi f\mu k} = \frac{1}{2ma}\,\frac{\sinh 2ma - \sin 2ma}{\cosh 2ma + \cos 2ma} \quad . \quad . \quad (1)$$

$$\frac{L_e}{\mu k} = \frac{1}{2ma}\,\frac{\sinh 2ma + \sin 2ma}{\cosh 2ma + \cos 2ma} \quad . \quad . \quad (2)$$

Since these equations are derived on the assumption that the core consists of homogeneous plane sheets, they can be used for laminated cores only when the ratio of lamination thickness to lamination width is small.

When $2ma$ is less than 1 or greater than 5, the equations can be considerably simplified. Fig. 1 shows that, in the former case, a linear relationship is obtained

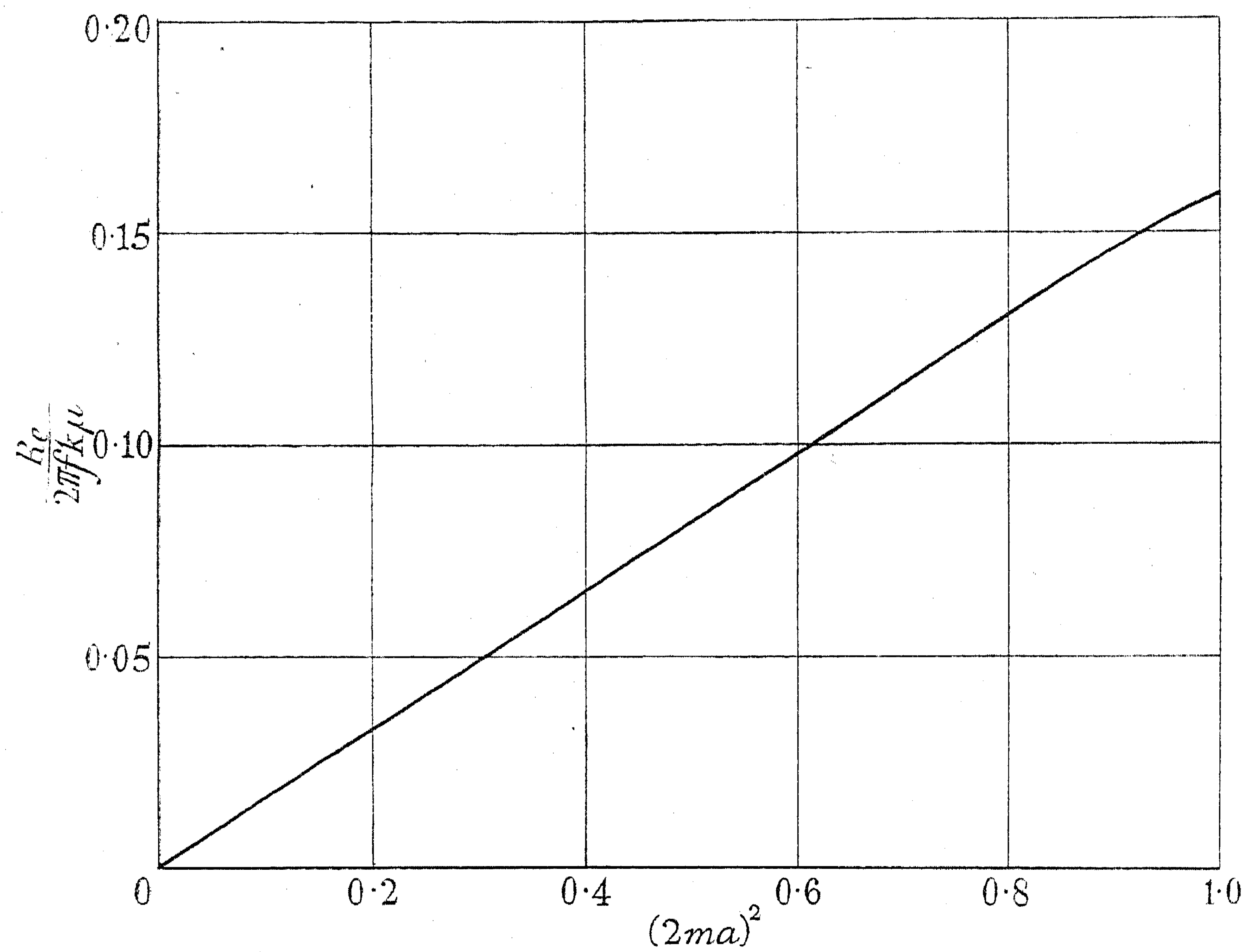


Fig. 1

between $R_e/(2\pi f\mu k)$ and $(2ma)^2$, and that, as a result, equation (1) can be written in the form

$$\frac{R_e}{2\pi f\mu k} = 0\cdot1625(2ma)^2 \quad . \quad . \quad . \quad . \quad (3)$$

or

$$\frac{R_e}{2} = \frac{16\cdot4\pi^4 ka^2\mu^2}{\rho} \times 10^{-10}$$

$$= 0\cdot205\pi^3k^2\mu^2p \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

From equation (2) we obtain

$$\frac{L_e}{\mu k} = \frac{120 + (2ma)^4 + \ldots}{120 + 5(2ma)^4 + \ldots}$$

so that, for values of $2ma$ less than $0\cdot7$, $L_e(\mu k)$ does not differ from unity by more than 1 per cent. Consequently, for frequencies which enable the condition $2ma < 0\cdot7$ to be satisfied, the eddy currents will produce no appreciable shielding effects.

When $2ma > 5$, $\sinh 2ma = \cosh 2ma >> 1$. Equations (1) and (2) therefore simplify to

$$\frac{R_e}{2\pi f\mu k} = \frac{L_e}{\mu k} = \frac{1}{2ma}$$

or

$$pR_e = p2\pi fL_e = 2ma \quad . \quad . \quad . \quad . \quad (5)$$

The theory of eddy-current shielding for plane sheets can therefore be verified when the shielding effect is small by plotting R_e against f^2 and checking equations (4); and, when the shielding effect is large, by plotting pR_e and $p2\pi fL_e$ against $(2ma)$ and checking equation (5).

PRACTICAL CONSIDERATIONS

When the impedance measurements are made on a core consisting of non-magnetic laminations whose ratio of thickness to width is small, frequencies of the order of 1 000 kc. are necessary to explore satisfactorily the region in which $2ma < 1$. Frequencies exceeding 10 000 kc. are therefore required for the measurements corresponding to the condition $2ma > 5$. The difficulty of obtaining accurate results in the latter case lies partly in making the measurements themselves and partly in accounting for the errors arising from the resonance condition introduced by the coil shunting capacitances. In view of this it was decided that, although laminations thin enough to simulate the conditions of the plane sheet could be used to verify equation (4), much thicker laminations rather than higher frequencies would have to be employed to satisfy the condition $2ma > 5$. The use of such laminations meant, however, the extension of equation (5) to take into account the ratio of lamination thickness to lamination width. This was effected by the analysis outlined below.

EQUATIONS FOR THE THICK SHEET

By the principle of duality, the equation for the current streamlines which are set up in the rectangular cross-section of a plate by a flux normal to its surface will be the same as the equations for the lines of induction which are set up in a rectangular rod of infinite permeability by a current flowing through it, i.e. one in which all the lines are confined to the rod. The equation for the lines of induction is*

$$x^2 + \sum_{n=0}^{n=\alpha} \frac{32a^2(-1)^n}{(2n+1)^3 \cosh(2n+1)\frac{\pi b}{2a}} \cdot \cosh(2n+1)\frac{\pi y}{2a} \cdot \cos(2n+1)\frac{\pi x}{2a} = K^2 \quad . \quad (6)$$

where K is a constant for any given line. To obtain its value for any given line which intersects the x-axis at, say, $x = x_1$, we put $y = 0$ and $x = x_1$ in equation (6), and solve for K. For example, the value of K corresponding to the boundary of the section which is a line of induction is obtained by writing $x = a$ and $y = 0$, giving $K = a$. In our case, therefore, the current streamlines do not form similar figures, so that the possibility of a complete mathematical solution of the problem of the shielding effects due to eddy currents in a thick plate seems rather remote.

It is possible, however, to derive a solution for the case when the shielding effects are large by considering the much simpler problem of the elliptical core. When $2ma > 10$, the resistance and inductance of a coil wound on such a core are (see Appendix 1) given by

$$pR_e = p2\pi f L_e = 2ma\left(1 + \frac{a}{b}\right) \quad . \quad . \quad . \quad (7)$$

Since equation (7) reduces to equation (5) when we write $a/b = 0$, the assumption that it may also apply to the rectangular core seems justified.

When $2ma < 1$, the solution for the elliptical core gives

$$\frac{R_e}{2\pi f\mu k} = 0\cdot25(2ma)^2 \cdot \frac{1}{1+(a/b)} = 0\cdot25(2ma)^2, \quad \text{when } \frac{a}{b} = 0 \quad . \quad . \quad . \quad . \quad (8)$$

Comparison of equation (8) with equation (3) shows that, when the shielding effect is small, the results of the analysis of the elliptical core can no longer be expected to hold for the rectangular one.

It appears, therefore, that, although a complete solution for thick sheets seems impossible, equation (7) (subject to experimental confirmation) does provide us with a solution when the shielding effect is large, and consequently with the means of verifying the theory of eddy currents in plane sheets when $2ma > 5$. A more rigid solution in the case of the rectangular core may be possible, when the shielding effect is large, by the method of the Schwartz–Christoffel transformation on the lines adopted by Cockcroft* to solve the problem of the skin effect in rectangular conductors at high frequency. An experimental verification of Cockcroft's equations has been given by W. Jackson.†

This point was not pursued, however, because, as is shown below, over the frequency range employed excellent agreement was obtained between the measured values on the rectangular cores and those calculated from equation (7).

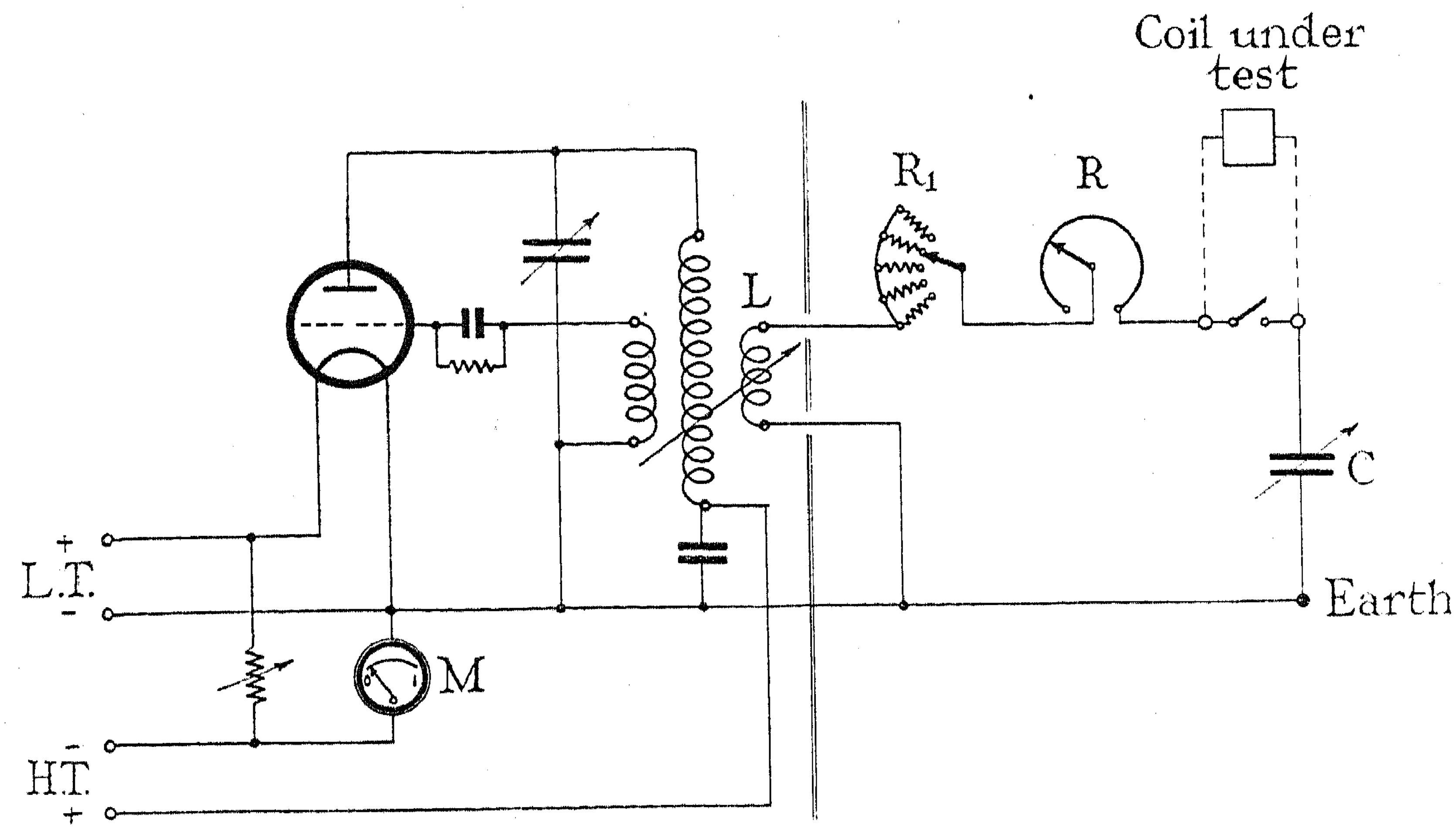


Fig. 2

EXPERIMENTAL PROCEDURE

The tests were made on cores built up of non-magnetic laminations carefully insulated from each other and wound with $3 \times 3 \times 30 \times 0\cdot07$-mm. litz wire. To minimize the possibility of leakage errors, the spacing between turns was made as small as possible. Also the ratio of lamination width to core radius was made small enough for the variation of m.m.f. throughout the lamination thickness to be negligible.

The resistance and inductance of each coil were measured by substitution, the arrangement of Fig. 2

* M. Strutt: *Archiv für Elektrotechnik*, 1927, vol. 18, p. 190.

* *Proceedings of the Royal Society*, A, 1929, vol. 122, p. 534.

† *Philosophical Magazine*, 1934, vol. 18, p. 433.

being employed in the following way. The circuit is first tuned to resonance with the unknown coil in circuit, the backed-off meter M being used as the indicator. The coil is then short-circuited and the circuit re-tuned, the slide-wire R and, if necessary, the fixed resistances R_1, being adjusted at the same time to obtain the original deflection in M. The resistance of the coil is then given by the alteration in $(R + R_1)$, and the inductance by $\frac{1}{\omega^2}\left(\frac{1}{C_1} - \frac{1}{C_2}\right)$, where C_1 and C_2 are the respective readings of the tuning condenser with and without the coil in circuit.

The resistance measured in this way is made up of the resistance of the winding proper plus the resistance due to the presence of the core. The former was measured separately in each case by transferring the wire to a wooden core of the same dimensions as the corresponding metal one. The inductance is made up of the value due to the presence of the core plus the value due to the air space within the winding. The latter was evaluated by subtracting the calculated value of k from the inductance of the coil when measured at 50 cycles per sec. in order to avoid any shielding effect.

To minimize possible errors due to the stray capacitances to earth of the various components, the indicated position of the coil under investigation was chosen, and, for each test frequency, the value of L/C was made as small as possible.* Also, to avoid unnecessary complications in making the measurements, the frequency range was confined to 100–1 000 kc.

Altogether seven coils, whose particulars are given in Tables 1A and 1B, were measured. Coils A, B, and C, were employed to verify the theory when the shielding effect is small, the coils D, E, F, and G, when the shielding effect is large.

EXPERIMENTAL RESULTS

Fig. 3 shows R_e, the resistance due to the core alone, plotted against f^2 for coils A, B, and C, and Fig. 4 shows pR_e plotted against $(2ma)$ for coils D, E, and F. The corresponding curve for coil G is given in Fig. 5, and, for convenience of comparison, part of it has been included in Fig. 4. The relation between $(p . 2\pi f L_e)$ and $2ma$ for coils E and F is given in Fig. 6. The inductance curves for coils D and G are not included, because it was found impossible to make the measurements satisfactorily. The total variation of inductance which could be expected for these coils over the given frequency-range formed such a small percentage (about 10 per cent at the higher frequencies) of the inductance of the coil due to the air space within the winding that, in spite of the care taken, the differences in inductance between successive frequencies were smaller than the experimental error which could be reasonably expected. Even in the case of coils E and F it was difficult to evaluate the inductance due to the core closer than to about 5 per cent at 100 kc. and 10 per cent at 1 000 kc. In the case of coils A, B, and C, no measurable change of inductance could be detected over the frequency range.

Table 1A

Coil	Material	Thickness	Measured resistivity	Number of rings	Area of cross-section	Number of turns	k	p	$2ma$ at $f = 10^6$ cycles/sec.
		cm.	microhms per cm. cube		cm.^{2}				
A	Copper	0·00698	1·915	211	1·47	114	$6{\cdot}96 \times 10^{-6}$	0·0229	1·01
B	Tin	0·0165	12·45	57	0·99	103	$3{\cdot}83 \times 10^{-6}$	0·0358	0·931
C	Tin	0·0254	13·10	71	1·80	108	$7{\cdot}65 \times 10^{-6}$	0·0405	1·396
D	Copper	0·142	1·91	9	1·62	126	$10{\cdot}15 \times 10^{-6}$	6·54	24·3
E	Zinc	0·310	6·42	5	1·97	156	$18{\cdot}89 \times 10^{-6}$	4·99	20·45
F	Tin	0·394	11·75	4	2·01	158	$19{\cdot}70 \times 10^{-6}$	4·21	22·79
G	Zinc	0·660	6·36	2	1·675	117	$9{\cdot}04 \times 10^{-6}$	47·6	52·00

It is seen that in each case a straight line from the origin can be drawn through the points, in accordance with the theory. Further, the summary of the measured values and the corresponding calculated ones given in Table 2 shows that excellent agreement between them is obtained. We can therefore conclude that, for non-magnetic materials, the validity of the eddy-current theory of shielding for plane sheets is established, and that, for sheets of any thickness, equation (7) will apply so long as $2ma > 10$.

Table 1B

DIMENSIONS OF RINGS, IN CENTIMETRES

	Coils A, B, and C	Coils D, E, F, and G
External diameter ..	12	11·42
Internal diameter ..	10	8·88
Mean circumference ..	34·5	31·9

So far as magnetic materials are concerned, since μ appears in the formulation of the theory only as a multiplier when the flux passing through the core is evaluated, there seems no reason to doubt that, for a homogeneous magnetic material, the equations can be used with complete confidence.

As previously mentioned, Peterson and Wrathall have, however, shown that, in practice, magnetic materials are rarely homogeneous, the inhomogeneity taking the form of a thin surface layer which they postulate has the

* See M. REED: *Wireless Engineer*, 1936, vol. 13, p. 248.

same resistivity but a uniform permeability much lower than that of the interior. To take this into account, they have obtained equations for the composite lamina-

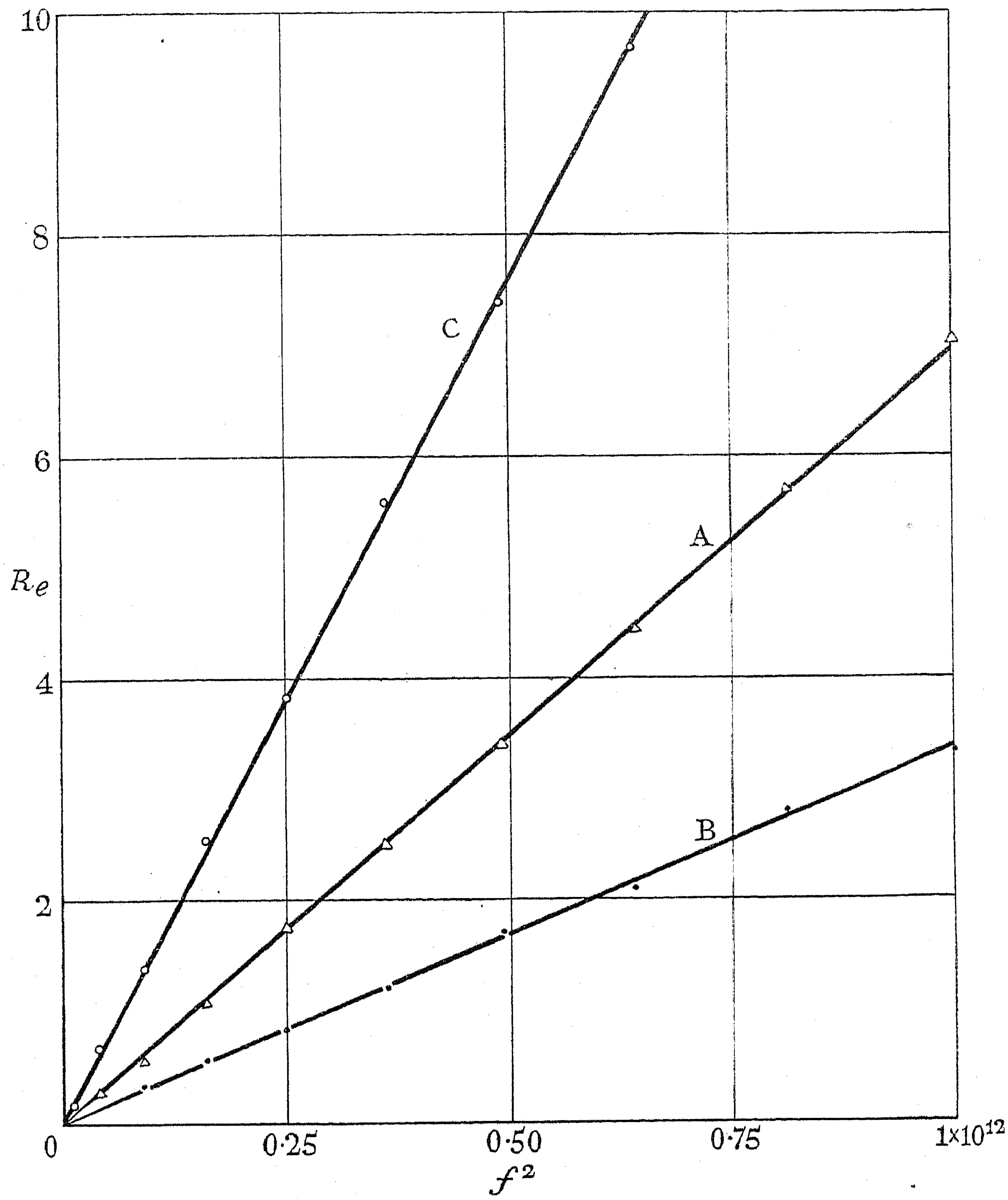


Fig. 3

Table 2

Coil	R_e/f^2, calculated from eq. (4) with $\mu = 1$	R_e/f^2, measured	Ratio, Calculated / Measured	$pR_e/(2ma)$, calculated from eq. (5) with $\mu = 1$	$pR_e/(2ma)$, measured	Ratio, Calculated / Measured	$p \cdot 2\pi f L_e/(2ma)$, measured	Ratio, Calculated / Measured
A	$7 \cdot 12 \times 10^{-12}$	$7 \cdot 0 \times 10^{-12}$	1·015	—	—	—	—	—
B	$3 \cdot 37 \times 10^{-12}$	$3 \cdot 38 \times 10^{-12}$	0·9975	—	—	—	—	—
C	$15 \cdot 15 \times 10^{-12}$	$15 \cdot 2 \times 10^{-12}$	0·9975	—	—	—	—	—
D	—	—	—	1·112	1·115	0·999	—	—
E	—	—	—	1·244	1·225	1·015	1·26	0·9875
F	—	—	—	1·310	1·275	1·026	1·325	0·99
G	—	—	—	1·520	1·506	1·01	—	—

tion which provide the necessary modifications to the simple eddy-current theory. An experimental investigation of the validity of these equations is given in Appendix 2, where it is shown that agreement between the experimental results and the theory is obtained only when the screening effect due to the eddy currents is negligible. The results obtained when the screening effect is large indicate that the surface layer is not of constant permeability, there being either a grading of

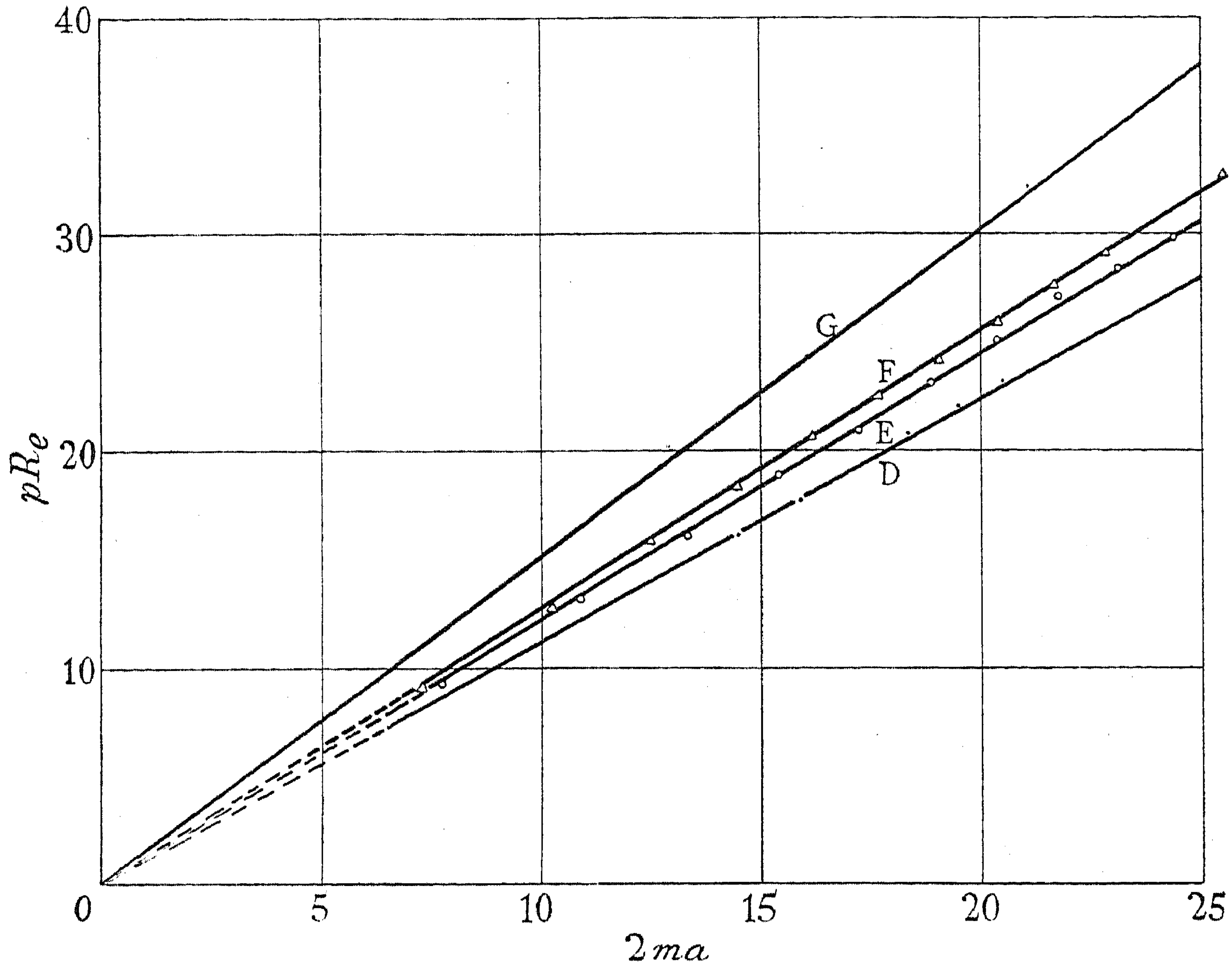


Fig. 4

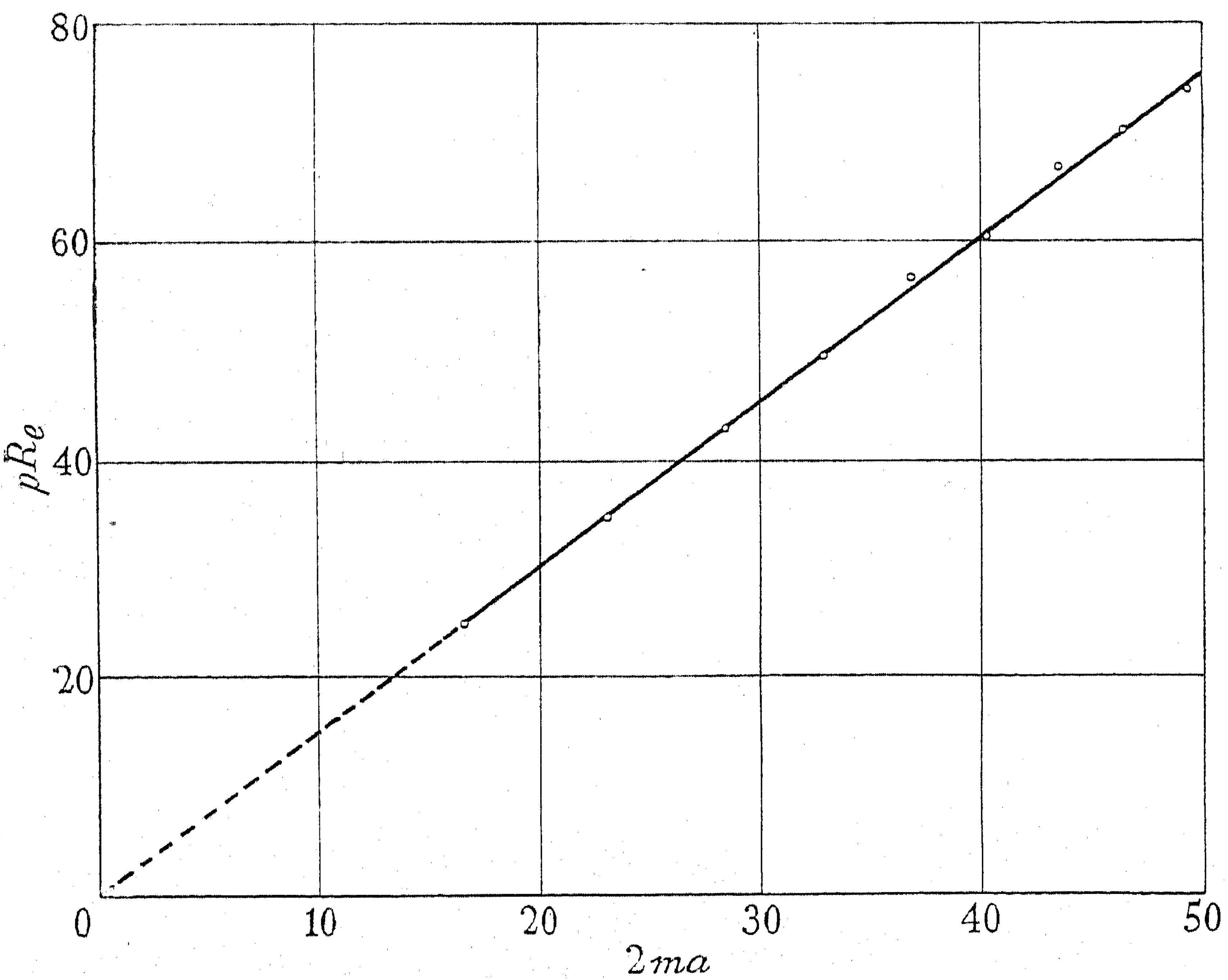


Fig. 5

permeability throughout its thickness or a number of component layers of different permeability. From the practical point of view, however, a study of the nature of the surface layer is somewhat academic, since we are concerned primarily with removing its undesirable effects. At present, the only way of accomplishing this seems to be to remove the layer by etching, so that it is necessary to know its total thickness. Appendix 2 shows that this quantity can be evaluated from the equation

$$a_2 = \frac{a}{2}\left(\frac{\tan \gamma}{\tan \beta} - 1\right)$$

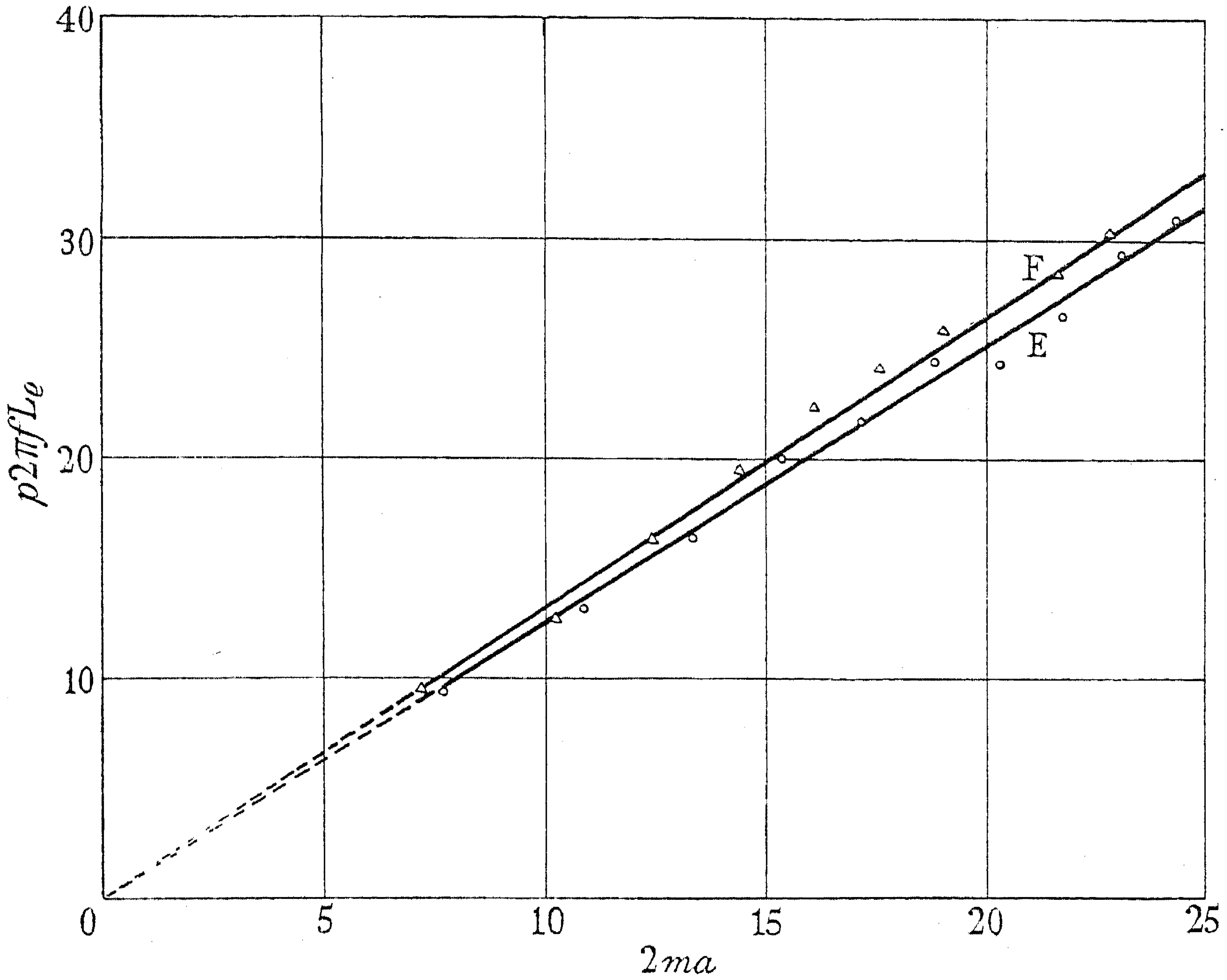


Fig. 6

where $\tan\beta = 26\cdot2\mu a^2/(10^9\rho)$, and $\tan\gamma =$ slope of line obtained by plotting $R_e/(\omega L_e)$ against f for values of $2ma$ less than unity.

ACKNOWLEDGMENT

The author is indebted to Dr. E. Mallett for suggesting the use of non-magnetic materials for the verification of the eddy-current theory, and for the interest which he has shown in this work. His thanks are also due to Messrs. Siemens Brothers and Co., Ltd., for permission to publish the paper.

APPENDIX 1

Eddy Currents in an Elliptical Core

The method of analysis employed in this Appendix follows the lines adopted by Scott* to solve the problem of eddy currents in a circular core. Strutt† has shown that the induction lines produced by a current flowing in an elliptical conductor of infinite permeability form ellipses which are similar to the boundary of the conductor. Therefore, it follows that in our case the current streamlines will also form similar ellipses. If we consider a shell formed by two such lines spaced by a distance dx in the way indicated by Fig. 7, then we can proceed as follows:—

For the depth of 1 cm. perpendicular to the plane of the cross-section, the resistance of the elementary shell to the flow of eddy currents is given by

$$R_x = \rho\left(\frac{\text{Circumference of shell}}{\text{Mean thickness}}\right) = \frac{\pi}{2}\rho\frac{(a+b)^2}{ab}\cdot\frac{x}{dx}$$

* *Loc. cit.* † *Loc. cit.*

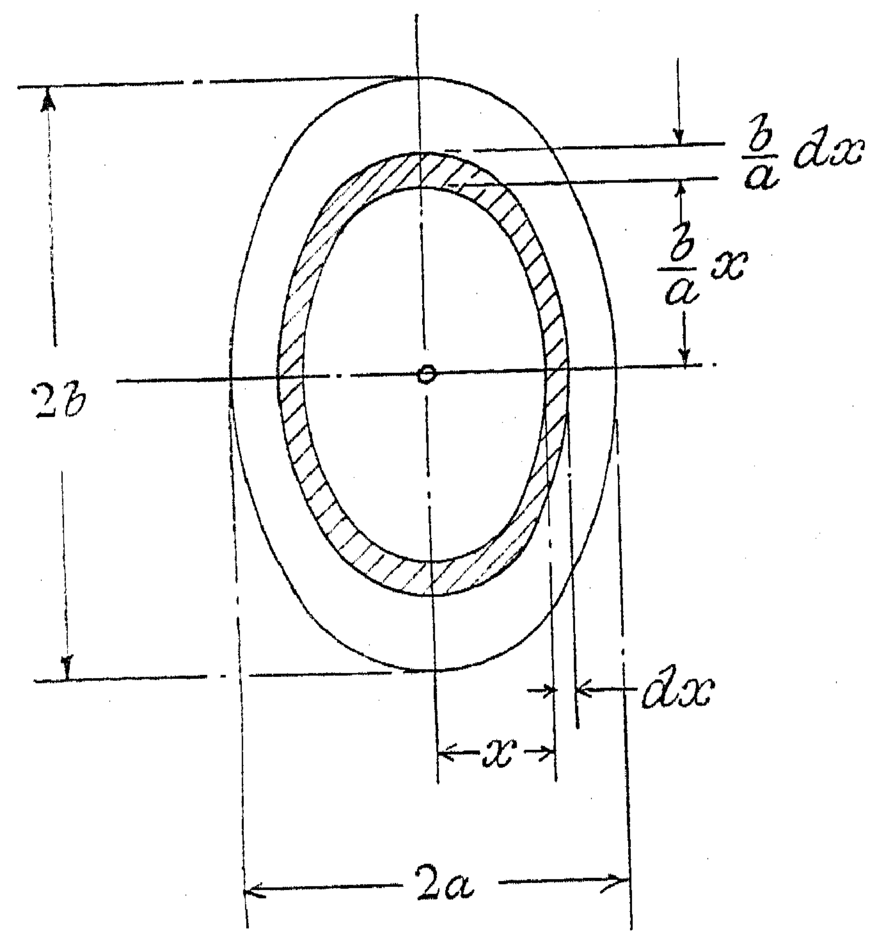


Fig. 7

$$\text{Area of shell} = \pi\frac{b}{a}[(x^2 + 2x dx) - x^2]$$
$$= 2\pi\frac{b}{a}x\,dx$$
$$\text{Circumference of shell} = \pi\cdot\frac{a+b}{a}\cdot x$$
$$\text{Average thickness of shell} = \frac{\text{Area}}{\text{Circumference}} = \frac{2b}{a+b}dx$$

If $E =$ e.m.f. induced in the shell by the flux normal to the cross-section, then

$$I_x = \text{Resulting current} = \frac{2E}{\rho}\cdot\frac{ab}{\pi(a+b)^2}\cdot\frac{dx}{x}$$

If B_x = flux density at x, then

$$\Phi_x = \text{total flux normal to shell}$$
$$= \pi\frac{2b}{a}B_x x dx$$

Therefore, the increment in voltage between the inner and outer surface of the shell is, vectorially

$$dE = -j2\pi f\,.\,\Phi_x 10^{-8}$$
$$= -j\,.\,2\pi^2 f\cdot\frac{2b}{a}\cdot B_x\,.\,x dx \times 10^{-8}$$

or
$$\frac{dE}{dx} = -j\,.\,2\pi^2 f\cdot\frac{2b}{a}\cdot B_x\,.\,x \times 10^{-8} \quad . \quad . \quad (9)$$

The increment in magnetizing force between the inner and outer surfaces of the shell is $-\frac{4\pi}{10}I_x$, and therefore

$$dB_x = \mu dH_x = -\frac{4\pi}{10}\cdot\mu\frac{2E}{\rho}\cdot\frac{ab}{\pi(a+b)^2}\cdot\frac{dx}{x}$$

or
$$\frac{dB_x}{dx} = -\frac{8}{10}\cdot\frac{\mu E}{\rho}\cdot\frac{ab}{(a+b)^2}\cdot\frac{1}{x} \quad . \quad . \quad (10)$$

From equations (9) and (10), E can be eliminated to give

$$\frac{d^2B_x}{dx^2} + \frac{1}{x}\cdot\frac{dB_x}{dx} - jC^2B_x = 0 \quad . \quad . \quad . \quad (11)$$

where

$$c = \sqrt{8}\,.\,2\pi\sqrt{\left(\frac{\mu f}{\rho\times 10^9}\right)}\frac{b}{a+b} = \sqrt{8}\,.\,m\frac{b}{a+b} \quad . \quad (12)$$

Equation (11) is identical in form with the one obtained by Scott for the circular core. We can therefore take over his solution and obtain, finally, for the inductance and resistance respectively,

$$\frac{L_e}{\mu k} = \frac{2}{ca}\cdot\frac{ber(ca)bei'(ca) - bei(ca)ber'(ca)}{ber^2(ca) + bei^2(ca)} \quad . \quad (13)$$

$$\frac{R_e}{2\pi f\mu k} = \frac{2}{ca}\cdot\frac{ber(ca)ber'(ca) + bei(ca)bei'(ca)}{ber^2(ca) + bei^2(ca)} \quad . \quad (14)$$

For $ca > 10$, we can write*

$$ber(ca) = \frac{e^{ca/\sqrt{2}}}{\sqrt{[2\pi(ca)]}}\left[\cos\left(\frac{ca}{\sqrt{2}}-\frac{\pi}{8}\right)+\frac{1}{8ca}\sin\left(\frac{ca}{\sqrt{2}}+\frac{\pi}{8}\right)\right]$$

$$bei(ca) = \frac{e^{ca/\sqrt{2}}}{\sqrt{[2\pi(ca)]}}\left[\sin\left(\frac{ca}{\sqrt{2}}-\frac{\pi}{8}\right)-\frac{1}{8ca}\cos\left(\frac{ca}{\sqrt{2}}+\frac{\pi}{8}\right)\right]$$

$$ber'(ca) = \frac{e^{ca/\sqrt{2}}}{\sqrt{[2\pi(ca)]}}\left[\cos\left(\frac{ca}{\sqrt{2}}+\frac{\pi}{8}\right)-\frac{3}{8ca}\cos\left(\frac{ca}{\sqrt{2}}-\frac{\pi}{8}\right)\right]$$

$$bei'(ca) = \frac{e^{ca/\sqrt{2}}}{\sqrt{[2\pi(ca)]}}\left[\sin\left(\frac{ca}{\sqrt{2}}+\frac{\pi}{8}\right)-\frac{3}{8ca}\sin\left(\frac{ca}{\sqrt{2}}-\frac{\pi}{8}\right)\right]$$

so that equation (13) simplifies to

$$\frac{L_e}{\mu k} = \frac{2}{ca}\cdot\frac{\frac{1}{\sqrt{2}}+\frac{1}{8(ca)}-\frac{3\sqrt{2}}{128(ca)^2}}{1+\frac{\sqrt{2}}{8(ca)}+\frac{1}{64(ca)^2}} \simeq \frac{\sqrt{2}}{ca}$$

* See N. W. McLachlan: "Bessel Functions for Engineers" (Clarendon Press, 1934).

and equation (14) simplifies to

$$\frac{R_e}{2\pi f\mu k} = \frac{2}{ca}\cdot\frac{\frac{1}{\sqrt{2}}-\frac{3}{8(ca)}-\frac{3\sqrt{2}}{128(ca)^2}}{1+\frac{\sqrt{2}}{8(ca)}+\frac{1}{64(ca)^2}} \simeq \frac{2}{ca}\left(\frac{1}{\sqrt{2}}-\frac{1}{2ca}\right)$$

For large values of (ca) we have, therefore, that

$$\frac{L_e}{\mu k} = \frac{R_e}{2\pi f\mu k} = \frac{\sqrt{2}}{ca} = \frac{1}{2ma}\cdot\frac{a+b}{b}$$

which can be expressed in the form

$$pR_e = p2\pi fL_e = 2ma\left(1+\frac{a}{b}\right)$$

When $ca < 1$, we can proceed as follows:—

By definition,

$$ber(ca) = 1 - \frac{(ca)^4}{2^2 4^2} + \frac{(ca)^8}{2^2 4^2 6^2 8^2} + \ldots$$

and
$$bei(ca) = \frac{(ca)^2}{2^2} - \frac{(ca)^6}{2^2 4^2 6^2} + \ldots$$

so that, for $ca < 1$, we can write as a close approximation

$$ber(ca) = 1, \quad ber'(ca) = -\frac{(ca)^3}{16}$$

$$bei(ca) = \frac{(ca)^2}{4}, \quad bei'(ca) = \frac{(ca)}{2}$$

Consequently, equation (13) simplifies to

$$\frac{L_e}{\mu k} = \frac{2}{ca}\cdot\frac{\frac{ca}{2}+\frac{(ca)^5}{64}}{1+\frac{(ca)^4}{16}} \simeq 1$$

and equation (14) simplifies to

$$\frac{R_e}{2\pi f\mu k} = \frac{2}{ca}\cdot\frac{\frac{(ca)^3}{16}}{1+\frac{(ca)^4}{16}} \simeq \frac{(ca)^2}{8}$$

For small values of ca we have, therefore,

$$\frac{L_e}{\mu k} = 1, \quad \text{and} \quad \frac{R_e}{2\pi f\mu k} = \frac{(ca)^2}{8} = \frac{1}{4}\cdot(2ma)^2\cdot\left(\frac{b}{a+b}\right)^2$$

APPENDIX 2

Investigation of Peterson and Wrathall's Equations

For the composite lamination, Peterson and Wrathall show that the equations corresponding to (1) and (2) are given by

$$A = \frac{\sinh\theta_2 \pm \sin\theta_2 + 2r(Y\cosh\theta_2 \pm X\cos\theta_2)}{\theta_2(1+K)\left[\cosh\theta_2 + \cos\theta_2 + 2r(Y\sinh\theta_2 - X\sin\theta_2) + r^2(X^2+Y^2)(\sinh\theta_2 \mp \sin\theta_2) + r_2(X^2+Y^2)(\cosh\theta_2 - \cos\theta_2)\right]} \quad . \quad . \quad (15)$$

where $A = L_e/L_0$ when the upper signs are used, and $A = R_e/(\omega L_0)$ when the lower signs are used;

$Y = \dfrac{\sinh \theta_1}{\cosh \theta_1 + \cos \theta_1}$;

$X = \dfrac{\sin \theta_1}{\cosh \theta_1 + \cos \theta_1}$;

$L_0 = \mu k =$ inductance, in henrys, of the coil at zero frequency due to the presence of the core alone;

$\theta = 2ma = 4\pi a\sqrt{\left(\dfrac{\mu f}{10^9 \rho}\right)}$;

$\theta_1 = 4\pi a_1\sqrt{\left(\dfrac{\mu_1 f}{10^9 \rho}\right)}$;

$\theta_2 = 4\pi a_2\sqrt{\left(\dfrac{\mu_2 f}{10^9 \rho}\right)}$;

$r^2 = \mu_1/\mu_2$;

$K = \mu_1 a_1/(\mu_2 a_2)$;

$a_2 =$ thickness of surface layer, in cm.;

$a_1 = (a - a_2)$;

$\mu_2 =$ permeability of surface layer;

$\mu_1 =$ permeability of interior.

When plotting curves for composite laminations, it is usual to use values of θ which are obtained from the measurement of the permeability at a frequency low enough to avoid all shielding effects due to eddy currents. Thus

$$\theta = 4\pi(a_1 + a_2)\sqrt{\left(\frac{\mu f}{10^9 \rho}\right)}$$

where
$$\mu = \frac{\mu_1 a_1 + \mu_2 a_2}{a_1 + a_2}$$

In practice, it can be assumed that $\mu_1 a_1 >> \mu_2 a_2$, so that this equation reduces to $\mu a = \mu_1 a_1$, and we can also write

$$1 + K = 1 + \frac{\mu_1 a_1}{\mu_2 a_2} \simeq \frac{a_1}{a_2} r^2$$

As in the case of the homogeneous plane sheet, equation (15) can be considerably simplified when $\theta_1 < 1$ and $\theta_1 > 5$. In the first case, it can be assumed that, since $\mu_1 a_1 >> \mu_2 a_2$, $\theta_2 < 0{\cdot}1$ when $\theta_1 < 1$. This enables us to write, to a very close degree of approximation,

$$\sinh \theta_2 = \sin \theta_2 = \theta_2$$

and

$$\cosh \theta_2 = \cos \theta_2 = 1$$

As a result, after making these substitutions and ignoring $\theta_2/[r(Y + X)]$ in comparison with unity, equation (15) simplifies to

$$\frac{R_e}{\omega L_e} = \frac{\sinh \theta_1 - \sin \theta_1}{\sinh \theta_1 + \sin \theta_1} + r\theta_2 \frac{\cosh \theta_1 - \cos \theta_1}{\sinh \theta_1 + \sin \theta_1} \quad . \quad (16)$$

If the first expression on the right-hand side of this equation is plotted against θ_1^2 for values of θ_1 less than unity, a straight line passing through the origin is obtained, whose equation is

$$\frac{\sinh \theta_1 - \sin \theta_1}{\sinh \theta_1 + \sin \theta_1} = 0{\cdot}166\theta_1^2 = \frac{26{\cdot}2\mu_1 a_1^2}{10^9 \rho} f$$

By writing out the terms of the second expression in their respective series, it can be shown that this expression approximates very closely to $0{\cdot}5r\theta_1\theta_2$. Consequently, equation (16) can be expressed in the form

$$\frac{R_e}{\omega L_e} = 26{\cdot}2\frac{\mu a^2}{10^9 \rho}\left(\frac{a_1}{a} + \frac{3a_2}{a}\right) f \quad . \quad . \quad (17)$$

after substituting for θ_1, θ_2, and r, and writing $\mu = \mu_1 a_1/a$. Therefore, by plotting $R_e/(\omega L_e)$ against f, we should obtain a straight line passing through the origin of slope, say, $\tan \gamma$. In the absence of a surface layer, equations (1) and (2) show that the line will have a slope of, say, $\tan \beta = 26{\cdot}2(\mu a^2/10^9)\rho$. It follows then from equation (17), by substituting $a_1 = (a - a_2)$, that

$$a_2 = \frac{a}{2}\left(\frac{\tan \gamma}{\tan \beta} - 1\right) \quad . \quad . \quad . \quad . \quad (18)$$

Consider now the form which equation (15) takes when $\theta_1 > 5$. In this case, it can be assumed that $\sinh \theta_1 \simeq \cosh \theta_1 >> 1$, which makes $Y \simeq 1$ and $Y >> X$. Equation (15) therefore simplifies to

$$\frac{a_1}{a_2} \cdot A = \frac{(1+r^2)\sinh \theta_2 + 2r\cosh \theta_2 \mp (r^2-1)\sin \theta_2}{\theta_2 r^2[(1+r^2)\cosh \theta_2 + 2r\sinh \theta_2 - (r^2-1)\cos \theta_2]} \quad . \quad . \quad . \quad . \quad (19)$$

Also

$$\frac{\omega L_e}{R_e} = \frac{(1 + r^2)\sinh \theta_2 + 2r\cosh \theta_2 - (r^2 - 1)\sin \theta_2}{(1 + r^2)\sinh \theta_2 + 2r\cosh \theta_2 + (r^2 - 1)\sin \theta_2}$$

from which $\omega L_e/R_e = 1$ when $\theta_2 = \pi$.

If θ_p is the value of θ when $\omega L_e/R_e = 1$, equation (19) becomes, when this condition is satisfied,

$$\frac{a_1}{a_2}\left(\frac{R_e}{\omega L_0}\right)_p = \frac{a_1}{a_2}\left(\frac{L_e}{L_0}\right)_p = \frac{1}{\pi r^2}\left(1 - \frac{1}{11{\cdot}55} \cdot \frac{r-1}{r+1}\right)$$

For the purpose of estimating the quantity in brackets, $r = 5$ can be regarded as a reasonable mean of the values likely to be met in practice. This gives

$$\frac{a_1}{a_2}\left(\frac{R_e}{\omega L_0}\right)_p = \frac{a_1}{a_2}\left(\frac{L_e}{L_0}\right)_p = \frac{0{\cdot}942}{\pi r^2} \quad . \quad . \quad (20)$$

When $\omega L_e/R_e = 1$, we obtain, by writing $\mu a = \mu_1 a_1$ in the expression for $r^2\theta_2^2$,

$$r = \frac{a_2}{\sqrt{(aa_1)}} \frac{\theta_p}{\pi} \quad . \quad . \quad . \quad (21)$$

Hence, from equations (20) and (21),

$$a_2 = a\frac{0{\cdot}942\pi}{\theta_p \tan \alpha} \quad . \quad . \quad . \quad . \quad . \quad (22)$$

where
$$\tan \alpha = \theta_p\left(\frac{R_e}{\omega L_0}\right)_p = \theta_p\left(\frac{L_e}{L_0}\right)_p$$

Equations (18) and (22) provide us with the means of verifying the theory of the composite lamination as propounded by Peterson and Wrathall. From the first equation the thickness of the surface layer can be determined by obtaining $\tan \gamma$ from the measured values of $R_e/(\omega L_e)$ for a range of frequencies which satisfies the condition $\theta_1 < 1$ (in practice, $\theta < 1$ provides a sufficiently close approximation), and calculating $\tan \beta$ from the

Table 3

Coil No.	Measured permeability (μ)	Measured resistivity (ρ)	Lamination thickness ($2a$)	Number of rings	Number of turns	Inductance (L_0)	θ at 10^6 cycles/sec.
1	1 323	$62 \cdot 8 \times 10^{-6}$	0·02525	25	70	$1 \cdot 486 \times 10^{-3}$	23·1
2	6 125	$42 \cdot 1 \times 10^{-6}$	0·0124	50	44	$2 \cdot 67 \times 10^{-3}$	29·7

Dimensions of rings: external diameter = 12 cm., internal diameter = 10 cm., mean circumference = 34·5 cm.

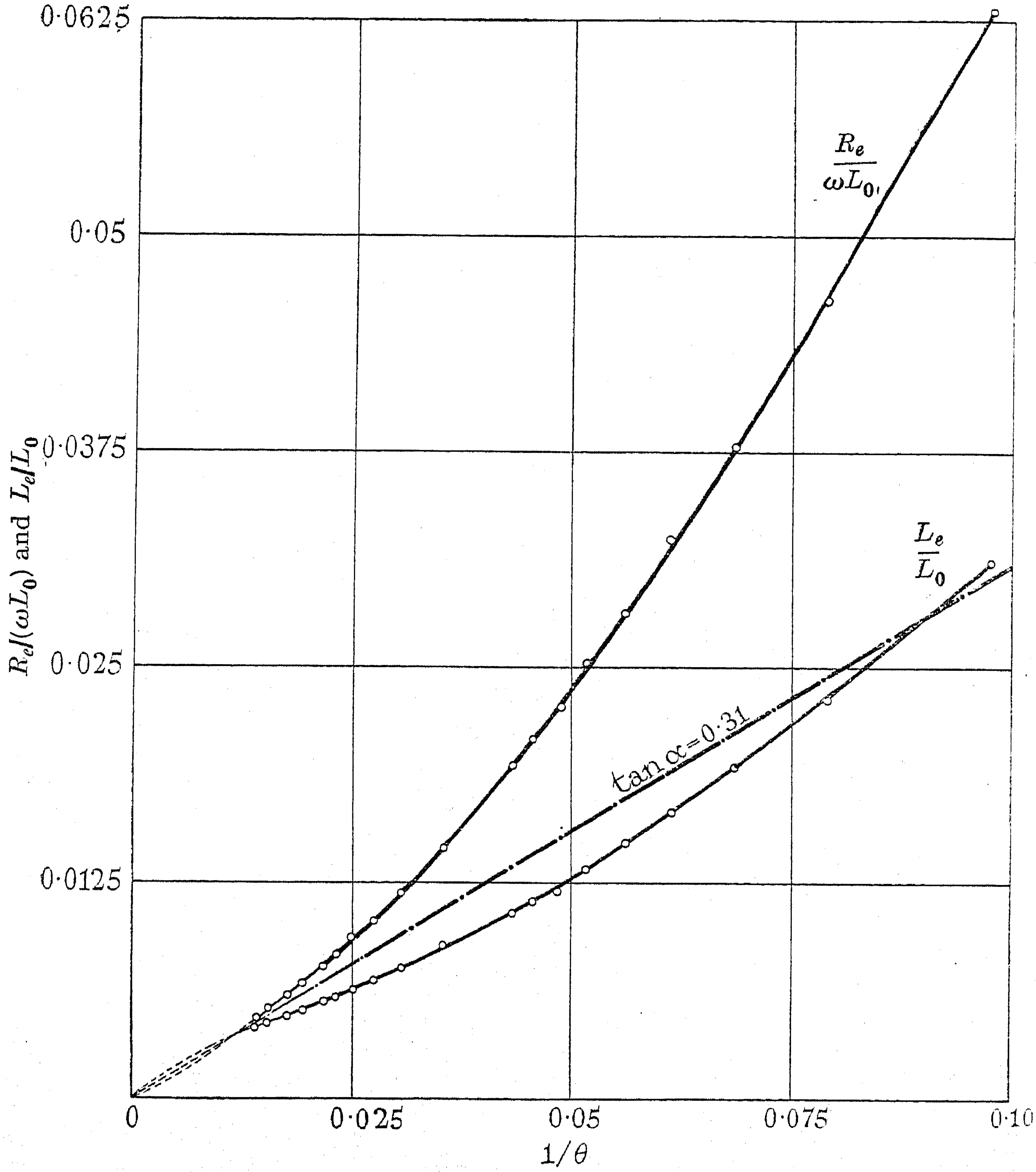


Fig. 8

constants of the coil under test. From the second equation the thickness of the surface layer can be evaluated by measuring $R_e/(\omega L_0)$ and L_e/L_0 for a range of frequencies which satisfies the condition $\theta_1 > 5$ (or $\theta > 5$) and determining θ_p and $\tan \alpha$ from the point of intersection of the two curves. The validity of the Peterson–Wrathall formulae would then be established if the same value for a_2 was obtained by the two methods.

This test was carried out on the two coils whose particulars are given in Table 3. The measurements for $\theta < \cdot 1$ were made by means of a standard audio-frequency bridge, and the results obtained are shown in Table 4.

Table 4

Coil No.	Tan γ, measured from curve	Tan β, calculated	a_2, in cm.
1	$0 \cdot 12 \times 10^{-3}$	$0 \cdot 088 \times 10^{-3}$	$2 \cdot 31 \times 10^{-3}$
2	$0 \cdot 258 \times 10^{-3}$	$0 \cdot 1465 \times 10^{-3}$	$2 \cdot 36 \times 10^{-3}$

Actually, the straight line obtained in each case for the graph between $R_e/(\omega L_e)$ and f did not pass through the origin. This phenomenon is well known,* and it is thought that the value of $R_e/(\omega L_e)$ at zero frequency is the measure of a loss (additional to the eddy-current losses) which arises from some form of molecular lag or viscosity. Since this value of $R_e/(\omega L_e)$ is usually very small, very little error in the evaluation of the surface-layer thickness is involved by ignoring the question of an additional loss, and it can be assumed that tan γ is given by the slope of the line as obtained by the measurements.

The measurements for $\theta > 5$ were made by using the circuit of Fig. 2, but, since the coil resistance was rather large, the measuring resistances and the coil under test were connected in parallel with the tuning condenser instead of in series.†

The curves obtained for coil No. 1 are shown in Fig. 8. Although the portions in the neighbourhood of the origin had to be obtained by interpolation, their point of intersection could be evaluated to a reasonably high degree of accuracy. Actually, from equation (19) we can expect the curves to intersect again, but, for the purpose of this investigation it is sufficient to assume that the loop encloses an area outside which the curves never fail. Similar curves were obtained for coil No. 2, and the results for both coils are given in Table 5.

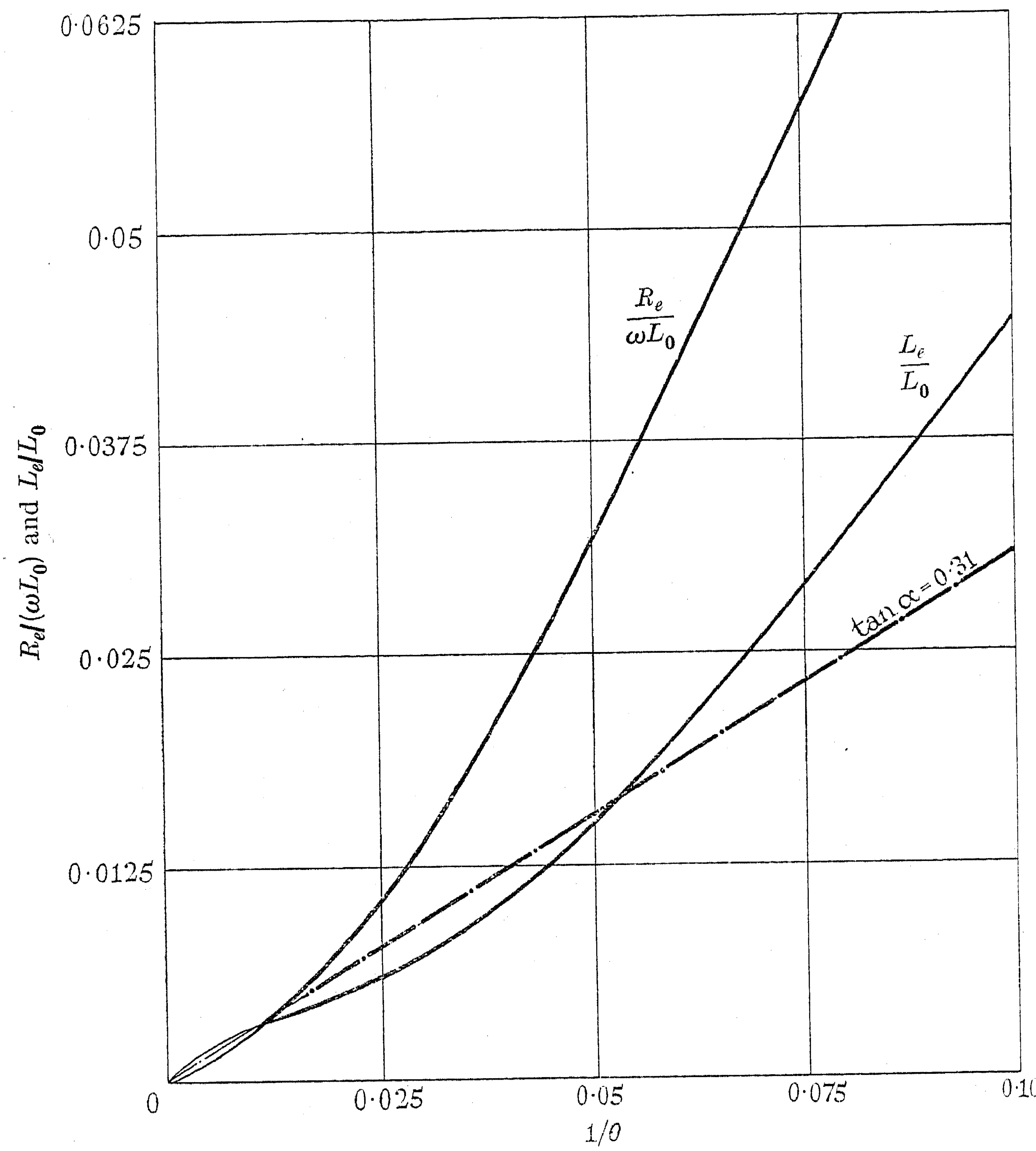


Fig. 9

Table 5

	Coil No. 1	Coil No. 2
$1/\theta_p$	0·01075	0·004
tan α	0·31	0·206
a_2	$1{\cdot}295 \times 10^{-3}$ cm.	$0{\cdot}357 \times 10^{-3}$ cm.
r	3·21	4·72

It is seen from Tables 4 and 5 that there is a disparity between the values for the surface-layer thickness

* H. JORDAN: *Elektrische Nachrichten-Technik*, 1924, vol. 1, p. 7.
† For further details see M. REED: *Wireless Engineer*, 1937, vol. 14 (May).

determined by the two methods which far exceeds any reasonable experimental error. Further, the curves of Fig. 9, which are calculated from equation (19) when the measured values of a_2 and r for coil No. 1 are used, give the same values for θ_p and $\tan \alpha$ as the corresponding curves of Fig. 8, but diverge considerably from the measured curves except in the neighbourhood of the origin, the discrepancy for any given value of θ increasing as θ decreases, i.e. as the frequency is reduced. A similar result is obtained for coil No. 2. On the other hand, when $\theta < 1$ there is close agreement between the measured curves [ignoring the value of $R_e/(\omega L_e)$ at zero frequency] and those calculated for the values of a_2 given in Table 4. It therefore appears that equation (19) is valid when the screening effect arising from the eddy currents is negligible, but not when it is large. A reasonable explanation for this is that the constant permeability of the surface layer postulated by Peterson and Wrathall does not obtain in the case of the coils under test. A possibility is that the permeability throughout the surface layer may be graded in such a way that the values of a_2 given in Table 5 correspond to the thickness of an equivalent layer of uniform permeability. Alternatively, the total surface layer may consist of a number of layers each of different permeability. Since the materials pass through a series of rolling stages in the process of manufacture, it is possible that each stage may add a surface layer of different permeability. If this is the case, the values of a_2 given in Table 5 will probably give the thickness of the outermost layer, because the frequency corresponding to the point of intersection of the $R_e/(\omega L_0)$ and L_e/L_0 curves is sufficiently high for the penetration of the flux not to extend beyond this layer. In any case, the values of a_2 given in Table 4 will correspond to the thickness of the total surface layer because, when $\theta < 1$, this layer will cause no appreciable attenuation to the wave travelling inwards from the outer edge of the lamination, so that any irregularities within the layer will not appear in the measurements.

DISCUSSION ON "TARIFFS FOR DOMESTIC AND BUSINESS PREMISES"* AND "THE PRICES FOR ELECTRIC SUPPLY"†

EAST MIDLAND SUB-CENTRE, AT NOTTINGHAM, 27TH OCTOBER, 1936

Prof. H. Cotton: The following personal experience is a good example of the attitude of the general public to the usual two-part domestic tariff. I happen to be one of the poor men (referred to by Prof. Miles Walker) who live in a large rambling house, and fortunately for me the rateable value is rather low, with the result that the fixed charge is also low. I have a colleague who has just moved from a similar house to a modern house in a fashionable district in which the rates are much higher. As a result his fixed charge, being based on the rateable value, is much higher than mine, the consequence being that the overall charge per unit is also much higher. Not being an electrical engineer, who would be conversant with the difficulties in framing an equitable tariff, he expresses very forcibly his dissatisfaction in being called upon to pay more for the same article than I do. This attitude is very common.

One answer to this objection is that electricity is more valuable from the social point of view to those who live in a fashionable district than to those in less favoured districts, and consequently a higher average charge per unit is fair. This argument is not justifiable, because electricity is just like any other commodity which is manufactured and sold; the fairest analogy is that of customers of all types buying the same kind of article from the same shop. In the shop there is no discrimination between customers, either from the point of view of ability to pay or from that of the utility value of the commodity supplied; all pay the same. On this analogy, the two-part tariff in which the fixed charge is based on rateable value, on the size of the house, or on any other entirely non-electrical consideration, does not appear to be logical. Admittedly it is convenient, but this is not very satisfactory to the consumer with a high fixed charge. It seems reasonable that the charges for electricity should be based only on the properties of electricity—its generation, transmission, distribution, etc.—and not on purely arbitrary and fluctuating considerations such as rateable value.

The desideratum is a uniform average price per unit for the same type of consumer in the same area. It is sometimes advocated that the charge should be uniform over the whole of the country, but, using again the analogy of the commodity, it appears reasonable that there should be differences, provided that these differences are not very great. It is obvious that local conditions cannot be uniform all over the country, and just as differences in price in a given commodity in, say, Nottingham and London, are justifiable, so also may differences in electricity tariffs be justifiable. The great discontent

* Paper by Mr. B. HANDLEY (see vol. 79, p. 505).
† Paper by Prof. MILES WALKER (see vol. 79, p. 510).

among users of electricity is due, not to the fact that there are such differences, but to the fact that they are so extreme. This is very clearly brought out in the two papers.

The main object of the papers, particularly that of Prof. Miles Walker, is to present the case of the consumer; this being so, I intend to raise a point which is never considered in the tariff. Continuing the analogy of electricity to any other commercial commodity, we all know that some commodities are of different grades, and that the higher the grade the higher the price. This is reasonable. Are there, then, different grades of electrical energy? From the point of view of utilization the answer to this is "yes," the grade being some function of the deviation from the declared voltage. The performance of consuming plant or apparatus is decidedly dependent on terminal voltage, and, if the voltage is down, the performance may deteriorate out of all proportion. The worst appliance in this respect is the most important from the point of view of the domestic consumer, namely the electric lamp. Fluctuations in voltage—usually in the wrong direction—are, of course, inevitable, but they are of very great importance to the consumer, and since they cannot be incorporated in any simple tariff it is only reasonable to expect that they should be reduced to an absolute minimum.

Everyone will agree with the authors that tariffs should be as simple as possible, and this applies particularly to a type of consumer mentioned by Mr. Handley. There is still a great deal to be done in regard to the electrification of farms, not only of the farmhouses but also of all the buildings, and since the average farmer cannot be bothered to understand a complicated tariff, or even may be suspicious of it, rapid extension in this direction necessitates a tariff of the simplest possible type.

Mr. E. G. Phillips: It is surprising that it is impossible to buy electricity in any form, or anywhere, on similar commercial terms to those relating to any other commodity. Many highly technical non-commercial tariffs are in force, and one of these reads as follows: "Where the number of units consumed within one year ending 31st March is less than 5 000, 9d. per unit for the first hour's consumption of the average maximum demand per day per quarter, and 4½d. per unit afterwards. Where 5 000 or more units are consumed within one year ending 31st March, 9d. per unit for the first hour's consumption of the average maximum demand per day per quarter, and 3½d. per unit afterwards." Another recent tariff reads: "A rental of £1 per kW per quarter of the consumer's maximum demand, subject to a minimum payment in respect of any quarter's kW demand equal to 50 per cent of the previous highest quarterly payment in respect of kW demand, plus: A unit price 0·35d. per kWh for all units up to 25 per cent load factor, and 0·30d. for all units in excess of 25 per cent load factor."

It is quite easy to understand the basis of such complicated tariffs. Technically they are correct and can be justified, especially from the supply authority's aspect, but is it not undesirable and very uncommercial for either the supplier or the customer to be unable to estimate the cost of the commodity on offer? Would it not be considered at least curious if a butcher, when asked his price for mutton, included in his explanation reference to the day of the week, the hour of the purchase, the proportion of bone or fat, the credit value of the wool taken from the carcase, the cost of hay or the rent of grass land, and whether the meat was to be eaten for the midday meal or kept for a late meal?

I have within the last few weeks endeavoured to make arrangements with supply companies for five institutions belonging to one authority, all within the same county, and where conditions and general demands are similar. It is anticipated that the price for the same service will vary from 1·39d. to 2·09d. per kWh.

Mr. C. A. Brearley: Mr. Handley quotes the figure of 20·3 per cent for the load factor of a housing estate in Hull. I understand that a similar figure has been obtained for a residential district in this area, and I should like to ask whether there is sufficient evidence to indicate that this (or some other) value may be taken as a general average for the country as a whole. The investigation could be pursued for particular industries, e.g. by considering an industrial district chiefly concerned with hosiery manufacture, etc. Perhaps the author can tell us whether this has been done. Consumers can be classified in a few main groups: (1) domestic, (2) industrial, (3) shops and business premises, (4) traction. It should be possible, without great difficulty, to obtain from representative districts average values of load and diversity factors for each group and important subgroup, and from such data to devise reasonably equitable tariffs, sensibly the same for similar districts throughout the greater part of the country, the basic recommended tariff in each group being a two-part tariff, with an alternative flat rate, and a sliding scale in the unit charge for relatively large consumers in some or (possibly) all groups. Since public supply authorities are in the privileged position of administering a monopoly granted by the State, consumers' engineers should establish the confidence of consumers by going out of their way to advise when a change from one tariff to another would be of advantage to the consumer.

As was mentioned by Prof. Miles Walker in discussing the wide variation in charges, some undertakings have gone to extreme lengths in price depreciation to secure load. The larger the area of supply and the wider the range in type of customer, the more difficult does it become to assess the incidence of the peak as between groups of customers, the narrower is the off-peak margin, and the more equitable is a two-part tariff based on the maximum demand of the individual customer and the diversity and load factors of his group.

Prof. Miles Walker recommends the rateable-value system as possibly the better for domestic purposes, Mr. Handley the size-of-house system. Would not the anomalies of each of these systems be removed more simply than by the method (*e*) mentioned by Mr. Handley, if both systems were adopted universally, each district recommending one as the basic scale and offering the other as an alternative? The basic scale would remain as at present in most districts, but probably in course of time the one more widely adopted would become the standard scale.

The majority of domestic consumers on a two-part tariff such as 15 per cent of rateable value plus ½d. per

unit, appear to enjoy very favourable terms. In view of the fact that many industries enjoy the bounties of the De-Rating and other Acts one can view such favoured terms with equanimity, but I would put in a plea here for another group of customers, namely tramway and trolley-bus undertakings. In 1933–34 the price of energy varied from 0·3d. per unit for 86 900 000 units per annum in Glasgow—where the Tramway Committee generates its own power—to 1·4d. per unit for a town taking 1 000 000 units per annum. Compare, for instance, the price of 0·825d. per unit paid by a certain municipal tramway for 17 500 000 units per annum at a load factor of 38 per cent with a small domestic load of 5 250 units at 0·707d. per unit, in a district where the domestic load factor is about 20 per cent. With the boom in the use of electricity in other directions, some supply engineers appear to have neglected these old customers and to have watched with complacency the competition of oil-bus transport. In 1933–34, municipal tramways (excluding London) consumed 493 800 000 units, equivalent to some 500 000 tons of coal. The energy consumption of a trolley-bus is about $1\frac{1}{2}$ times that of a tram for the same weight and schedule; the price per unit is therefore even more important for trolley-bus than for tramway systems. The matter is one for friendly and sympathetic discussion between the supply engineer and the transport manager, to enable the former to retain and extend the load, the latter to reduce the cost of the electrically-propelled vehicle in competition with the oil-fuel vehicle.

Mr. T. Rowland: I think we should try to get away from the idea of selling units and look at the question rather as one of selling service to the consumer.

Some years ago, when going into the question of a two-part tariff for domestic supplies, we had before us nearly every tariff in the country and eventually decided on a tariff based on rateable value in preference to floor area, largely because of the ease with which it was possible to collect data on which to base our charges. The rateable value of all existing domestic consumers was obtained, and against each was tabulated the annual consumption of current for different purposes. We thus ascertained the average consumption for premises of the same rateable value, on which we based the fixed charge. It was obvious that a fixed percentage on the rateable value was not equitable as between a house of a high rateable value and one of low rateable value, and therefore the fixed charge was graduated. This was done by adding a uniform fixed sum on to the percentage of rateable value, the tariff adopted being a fixed charge of $12\frac{1}{2}$ per cent of the rateable value plus £1 per annum, plus 1d. per unit for current consumed. This tariff offered an advantage to consumers who made reasonable use of the supply as compared with the flat rate of 8d. per unit, but the flat rate was reduced, and in line with the reduction a discount of 10 per cent was granted to the two-part tariff consumer. A certain amount of progress was made with this two-part tariff, but there was a tendency for consumers to be rather suspicious of it. About 18 months ago, further reductions in prices were made; the unit charge under the two-part tariff was reduced to $\frac{1}{2}$d. per unit, and the whole tariff was made subject to a discount of 10 per cent. There is no longer any difficulty in inducing consumers to adopt the two-part tariff, and we are deriving benefit from it. During the June quarter of 1936 the sales to domestic consumers under this tariff were nearly 70 per cent greater than during the corresponding period of the previous year.

Both papers seem to make very little reference to the market value of the supply. I think that in framing tariffs we should aim to sell our energy at a price which covers the cost and allows as large a margin of profit as the market value will permit.

With reference to the last paragraph of Prof. Miles Walker's paper, I think much could be achieved by means of tariffs to encourage consumers to use appliances at times of light load, or alternatively to spread their consumption over longer periods. As an instance, we have a consumer who uses an electric furnace consuming about 600 000 units per annum under a restricted-hour agreement which does not permit its use on the peak load. Prof. Miles Walker's battery-traction idea, however, does not seem to be quite a practical proposition.

Respecting the suggestions made by previous speakers that electricity should be sold in the same way as other commodities, we have a good example of this idea in the telephone service where, irrespective of the number of calls made, we pay a fixed annual charge plus a unit charge per call. I feel it would be quite equitable to work on the same lines as regards the sale of electrical energy.

Mr. R. G. Payne: I would appeal for some simple method of charging for electricity, which the consumer regards as purely a commodity. When a consumer buys a "unit" he seldom appreciates that its price has to cover its share of the generating station, switchgear, mains network, etc.; it is simply an "article," from his point of view.

Mr. Rowland referred to electricity as a service. I agree. So is transport, but one could not charge a passenger a two-part tariff—so much for the road he travels upon, and so much for the journey. I feel that if a simple form of charging for electrical energy can be found, business will increase both for the supply authorities and for the electrical industry as a whole.

Mr. R. B. Giles: The figures for Oxford which Prof. Miles Walker quotes should be a source of inspiration to those timorous supply authorities who have seen ruin in the prices of 1d. per unit or less for domestic consumers which the more progressive and prosperous authorities have been quoting for the last 10 years. Many of the previously backward undertakings, of course, have recently brought their tariffs into line with generally-recognized rates for domestic services, and $\frac{3}{4}$d. and even $\frac{1}{2}$d. per unit are now fairly common. There is a variation in fixed charges which is understandable.

I think electricity supply suffers over-much from the engineer, and has little enough true commerce in its make-up. In the past the reaction of the consumer to tariffs received little or no consideration, and many existing tariffs are thus psychologically unsound. The average domestic two-part tariff comprising a fixed charge and unit charge falls under this heading. In the early days we found an excuse for such a device in the telephone system, entirely ignoring the fact that comparatively few of our domestic consumers utilized the

telephone and the majority were therefore entirely unfamiliar with the system of charge.

While domestic consumers readily adopt the two-part tariff because it is cheaper to do so, it is not easy to convince the average domestic consumer of the necessity for his contribution towards the undertaking's capital charges. The necessity for the fixed charge is rapidly disappearing, if indeed it has not already done so.

Looking at electricity supply nationally, we have in the grid a huge reservoir of power which is to the supply industry what the gas-holder is to the gas industry. Peak loads are floating between base-load stations, and kW demand charges and quarterly fixed charges, which are so frequently an annoyance to consumers, must ultimately disappear. It looks as though they are only retained so far as they secure the grid and supply authorities their capital charges. These principles approved, the most simple, the fairest, and, therefore, the most popular, form of tariff can be agreed upon, namely the flat rate per unit (kWh).

I do not agree with Prof. Miles Walker's suggested use of maximum-demand indicators. The introduction of mechanical means for controlling diversity is not only unnecessary but profoundly annoying to the public. Experience has clearly shown that the diversity factor of an unrestricted domestic supply is high. While I approve of Prof. Miles Walker's comments anent load factor, I doubt the likelihood of developments in the electric motor-car, particularly if 20 miles is to be the maximum between refills.

Mr. R. C. Woods: Mr. Rowland referred to the telephone-service tariff as comparable with the domestic electricity tariff. Now the material difference is that with the telephone each individual consumer has his own lines connecting direct to the exchange building, and he cannot be tapped to a main feed. The capital cost of telephone lines and instruments is much greater than that involved in providing a domestic connection. The relation between capital and consumption costs is therefore decidedly different in the two cases.

With regard to the question of floor-area and rateable-value assessments, many people, especially in this area, are a little suspicious of the rateable value, as it is not a fixed quantity. It has been their experience that when rates approach that limit where the ratepayer raises serious objection to further increase, a grand reduction of rates is staged, accompanied by a general increase in the assessments. Also, the increased assessments mean higher water and electricity charges.

Six or seven weeks ago I wrote to a supply authority asking for particulars of the basis on which they fixed the standing charge in a particular 4- or 5-mile area, and whether it remained the same throughout that area. Their reply was that they would be pleased to quote me for my property. Further correspondence elicited the statement that the charge was based on area and that the basis remained uniform for the district, but that it could not be disclosed because of the necessity of maintaining the confidential relationship between consumer and supplier. This kind of secrecy gives one no confidence in the statement that the basis is uniform.

Another point to which I would draw attention is the position regarding meter rents. For my domestic-supply meter I am charged a rent of 2s. per quarter. I have had this meter over 12 years, and beyond reading it has received no attention throughout that period. A meter can be bought in the open market for 33s., and I have heard that supply authorities pay 18s. or less per meter. A substantial sum was paid for the initial connection, so the rent charge can be accepted as relating solely to the meter.

Mr. J. P. Tucker: The remarks of many of the previous speakers have not presented the efforts of supply authorities in a fair way. It is surely correct to say that discouraging tariffs are now the exception rather than the rule. While the size-of-house and the rateable-value tariffs are not completely satisfactory, the supply engineer, after having given serious thought to this problem, cannot think of a better. Whatever is done, due regard must be given to the multiplicity of tariffs already in existence.

About 4 years ago I was responsible for a new scheme covering approximately 225 square miles, and, having regard for the fact that eight different rating authorities were concerned, I considered it wise to adopt an area basis for the fixed charge. The undertaking with which I am associated at present has already adopted the rateable-value basis, however, and I should strongly discourage any suggestion to change that system.

A bright future for the road-vehicle load is given us in the paper by Prof. Miles Walker, and he would be indeed a bold man who would dare to challenge this forecast. It may be that road and rail load will account for a very high percentage of the electricity consumption of the future.

Mr. F. K. Fowkes: The main point about the charges for electric supply has not yet been mentioned. It is this: Are the supply authorities trying to achieve the complete electrification of the country, or are they trying to get as much money as possible out of the consumer? If the first supposition is correct, naturally the lowest economical price should be charged. The greatest revenue to the supply undertakings comes from the consumers who pay about £4 a year, and yet Prof. Miles Walker's sample house gives an annual revenue of £18; I suggest that in England there are not a great number of houses which give a revenue of that figure at the moment. I should like to ask whether, supposing his fixed charges were reduced, his revenue would rise above £18. A great number of consumers in this district are miners and they do not want electricity for heating or cooking, as they get their coal practically for nothing. They are prepared to pay about 1s. 6d. a week, however, for lighting by electricity, independent of the type of tariff.

Mr. Handley says that the development of the prepayment meter is complicating the tariff question, and that the ideal state is where all supplies are given on a two-part rate. There are, however, many more poor people than wealthy ones in this country, and some of them are not in a position to pay fixed charges but are prepared to take a supply of electricity through a slot meter.

Mr. J. S. Messent: The size-of-house or floor-area system of assessing a fixed charge appears to be regarded favourably, and it offers an excellent opportunity for undertakers to encourage a development which is greatly

to their advantage. I refer to the practice of installing fixed (inset or wall-mounted) electric fires in bedrooms of new houses. In contrast to portable fires, which may be used at all times, fixed fires in bedrooms are used normally early in the morning or late at night, and therefore do not add to the system peak load. Also, the absence of flues commits the tenants to electric heating, and in case of illness gives a load which is well distributed over the 24 hours. A logical method of promoting this tendency, which is already marked, would be to exclude bedrooms with fixed fires when assessing the floor area.

The adoption of this suggestion would help to counter the reproach that the supply industry is slow to encourage advantageous developments, as it was in the case of mains-operated radio, and as some undertakers are in regard to synchronous clocks.

Mr. Gilbert Smith (Loughborough): From a study of the various tariffs mentioned in the papers it is at once apparent that the two-part tariff is necessary when the load factor is poor and the peak loads are comparatively large. Such tariffs, however, do not necessarily tend to improve the load conditions, neither are they rational when applied in the form of rateable-value and floor-space tariffs.

A system used in a large north-country town has many good points and is arranged as follows for domestic purposes: All units used in the 6 months of the daylight-saving period are charged for at $\frac{1}{2}$d. per unit, and in the 6 darker months the same number of units can also be had at the same price; but units in excess of the summer quantity are charged for at 1d. per unit. It is at once evident to the consumer that if, for example, he had to pay for 1 000 excess units in the winter time he could have had 1 000 units in the summer time without further payment, and he would therefore increase his summer load in the next year by installing an electric kettle, water heater, or other apparatus, which probably would not be a necessity in the winter. This system is very simple and requires no special meters or elaborate accountancy, and at the same time definitely tends to improve the load and the load factor. It is also applicable to large and small houses, and to rich and poor consumers. The average price per unit also lies between $\frac{1}{2}$d. and 1d., which is comparable with the more reasonable tariffs given in the present papers.

Mr. J. F. Driver: I think that serious consideration should be given to the suggestion made by Prof. Miles Walker, that a method might be devised whereby the speed of the electricity meter could be varied. It should be possible to estimate the cost of generation for each hour of the day and night. If the meter speeds were adjusted to correspond to these costs the charges would be more equitable than those arrived at by merely taking into account, for example, the size of a man's house. It is clear, however, that some arrangement for taking into account individual load-factor problems would also need attention.

Some years ago the proposal was made that water heating should be arranged during off-peak-load times. In a small dwelling of the "council house" type, two rooms may be regarded as the principal rooms of the house. I suggest that these should be wired by means of 2-way switches and connected with a thermostatically-controlled water heater, so that when a room light was switched on a corresponding heater element would be switched off. This would mean that for these two rooms the load factor would be 100 per cent. In a large housing estate this arrangement would improve the load factor of the district.

Mr. C. A. Cameron Brown (*communicated*): From the report published in the *Journal* of the discussion before The Institution on Prof. Miles Walker's paper it is apparent that all the speakers assumed that it is vital to offer cheap electricity, but only one ventured to suggest that it should be cheap even when not used to the entire exclusion of coal, oil, or gas. How can Prof. Miles Walker be speaking on behalf of the "man in the street" when he puts forward, as reasonable, annual bills ranging from £18 to £32? Surely it is fundamentally more important to see that the 800-unit man has a reasonable price to pay than to accept complacently the position that the man who can only afford £1 or so per quarter has to pay more for a certain thing than the man who can pay £8 per quarter. This is a grave anomaly of which the supply industry ought to be ashamed. Moreover, is it not a fact that from coal to heat gas is the more efficient conversion and that, were the conservation of our natural resources borne in mind, the use of electricity would be prohibited for other than power and lighting purposes where gas is available?

We all know that the bugbear of the whole business of electricity supply is the standing charge. Mr. Kerr indeed takes the bull by the horns and suggests, playfully no doubt, that the standing charge should be the whole charge on an availability basis. Has not electricity supply charge reached a sufficiently advanced stage for a fundamental, if bold, step to be taken and electricity to be sold on the basis of a single low charge only? Let us eliminate the fixed charge, change a running charge of $\frac{7}{8}$d. into 1d. and $\frac{5}{8}$d. into $\frac{3}{4}$d., and leave the consumer to use his electricity on the only basis on which he can know exactly where he is. An experimental step on these lines would be one for one of the progressive municipalities to try.

Mr. B. Handley (*in reply*): Prof. Cotton points out the advantages of the rateable-value system in a big house, and of the size-of-house system in a smaller house in a fashionable district. These advantages might almost be said to be fundamental, but in my experience the difficulty of catering for consumers living in houses larger than they need is fast disappearing. The erection of large numbers of new houses, and the pressure of economic conditions, are leading people to have houses no larger than they need.

I do not agree that electricity is just like any commodity which is manufactured and sold. For instance, a consumer might occupy a lock-up garage with an annual consumption of a few units, yet he might telephone the electricity undertaking late one Sunday night to replace a blown fuse because he wanted to carry out a small repair job. I do not know of any other commodity to which such onerous service conditions are entailed. Statistics relating to calls to premises would surprise any one not conversant with these facts. My own experience is that for one reason or another, discarding

meter reading and so on, there would be about an average of one call per consumer per annum. In other words, an undertaking with 50 000 consumers would be called upon to send out men on 50 000 occasions during the year for service calls. It is true that many of these would be no more serious than that the consumer had forgotten to put the main switch on, but, nevertheless, if the electricity undertaking is to be successful, the calls must be attended to.

This point is brought out by Mr. Rowland, who properly emphasizes the selling of service. He mentions the telephone service as being analogous, with which I agree.

Doubts are thrown by some speakers upon the general principle of a two-part tariff, and it is suggested that an average price per unit should be ascertained and charged. Unfortunately, any attempt to charge an average price per unit (inclusive of standing and running charges) makes the price too high to secure the rapid expansion of the output of electricity which is so desirable.

One has to agree with those speakers who maintain that neither the rateable-value system nor the size-of-house system is logical. On the other hand, if the desired end can only be reached by illogical methods, then I suggest it is distinctly logical to adopt illogical methods. Again, do the public appreciate logical methods? I do not think so. If it were so, our coinage system, our weights and measures, and our present spelling, would have disappeared long ago.

I do not in any way agree with Mr. Giles's suggestion that the two-part tariff is psychologically unsound. Although in the very early days of two-part tariffs it might have been difficult to get consumers to adopt the method, at the present time the average consumer's reaction towards it is that it is an excellent way of securing a bargain. Consumers have actually come to like the system and demand it normally when moving from one area to another.

I agree with Mr. Tucker that supply authorities have now made considerable headway in simplifying tariffs. Discouraging tariffs are now becoming the exception, and I trust that the examples put forward by Mr. Phillips will soon be relegated to the past.

Prof. Miles Walker (*in reply*): I think the point made by Prof. Cotton as to the justification for the higher charge of electricity supplied for lighting is a good one. Mr. Phillips's instances of the wide differences in charges in similar districts confirms the result that I have arrived at by an examination of tariffs in various parts of the country.

In reply to Mr. Brearley, I still think that supply undertakings should give the consumer the choice of basing the fixed charge either on the rateable value or on the size of the house. I have shown that the fixed charge could economically be made much lower than it is at present in most districts.

Those speakers who take exception to the proposal as to the wide use of electric traction fed from hundreds of battery-providing stations dotted about the country have not gone into the economics of the proposal. They judge electric battery traction from the point of view of present conditions where every car has its own battery large enough to run all day without recharging and every battery owner has to pay for its depreciation. Under these conditions batteries have to be made 4 or 5 times as heavy as would be necessary under the proposal that I have put forward. If the batteries belonged to the supply undertakings there would be no reason why the weight per kilowatt-hour should not be reduced to one-third of what it is now. The lead frames of the plates would not be built to last many months. The remaking of plates from the old material would be carried out almost automatically by means of specially designed machinery. The plates would be designed to give the largest possible capacity for the smallest weight, and be remade when they began to fall to pieces. I hope shortly to be able to give The Institution some figures relating to batteries designed on this principle, and it will be seen that they put the case of electric battery traction in an entirely new light.

Several speakers object to my taking the sample house of fairly large size and my making the electricity bill as high as £18. If they will look at what I consider a fair and profitable basis for electric charges, namely 6 per cent of the rateable value and $\frac{1}{3}$d. to $\frac{1}{2}$d. per unit, they will be able to work out a very small annual bill for the small consumer.

DISCUSSION BEFORE THE MERSEY AND NORTH WALES (LIVERPOOL) CENTRE,* AT LIVERPOOL, 16TH NOVEMBER, 1936†

Mr. R. A. S. Thwaites: The fundamental conditions for sound tariffs appear to be three in number: First, they must in the aggregate yield an adequate financial return, whether the undertaking be company- or municipally-owned; although, as Mr. Handley states, there will inevitably be some consumers whose supplies are unremunerative. Secondly, they ought to be so designed as to attract the maximum amount of business. Thirdly, they should be equitable, as between one class of consumer and another.

It is the endeavour to comply with these conditions which mainly results in the wide variety of tariffs in force throughout the industry. The matter is further complicated because in many cases the relationship between the various tariffs of an undertaking is determined by extraneous circumstances, e.g. ownership of a gas undertaking, or even the particular interests of the majority of members of the electricity committee. For example, in the discussion on this paper before The Institution Mr. Westlake referred to an undertaking where the lighting price is 3d. and the heating price 2d. per unit. Such tariffs neither attract the maximum amount of business nor are they equitable as between one consumer and another. We must not, however, go to the other extreme. It is at present the fashion to regard a domestic tariff with a running charge of $\frac{1}{2}$d. as the ideal tariff, but unless the fixed charge is kept well up we have the anomaly of domestic consumers obtaining

* Joint meeting with the Liverpool Engineering Society.
† Only the paper by Mr. Handley ("Tariffs for Domestic and Business Premises") was discussed at this meeting.

their energy at prices considerably below those paid by large manufacturers for energy for motive power, which again does not seem equitable. In connection with the plea which has been made for uniformity in the basis of two-part tariffs, I would point out that once a particular method has become established it is difficult to make a change without giving rise to considerable dissatisfaction.

I should like to ask Mr. Handley, and also those who intend to take part in this discussion, to give their experience regarding two-part prepayment meters, which have great possibilities in catering for those consumers whose financial circumstances do not enable them to meet quarterly accounts. At present a variety of meters are available for such purposes. There is the two-rate meter, which has certain advantages, but does not record true units. There is also the load-rate meter, which automatically varies the price per unit when the load exceeds a predetermined amount. There is further a fixed-charge collector which can be used in conjunction with a standard prepayment meter, while in some districts it has been found satisfactory to fix a simple coin-box on the wall and rely on the consumer to place the fixed charge in the box each week. Finally, there are two classes of two-part tariff prepayment meters, namely those which collect arrears of fixed charges and those which do not.

Mr. O. C. Waygood: It seems that we shall have to accept for some time the two-part tariff system in charging for electrical energy, and if this system is simple in design and in application there is no reason why it should not be generally accepted. There are far too many complicated systems in vogue at present: supply authorities should standardize on two systems, one applicable to the domestic user and the other for business purposes.

It is not difficult to differentiate between domestic and business supplies, but complications are added in differentiating between different classes of business, and the various sections of the supply industry hold very divergent views on this point. For business purposes there is no question that the maximum-demand system in the end must be equitable to all concerned, and whether the maximum load taken is in "light" or in "power" should not be the determining factor in fixing a tariff.

For domestic purposes either building area or floor area should be the basis for assessing the fixed portion of the charge; and, for preference, building area. Rateable value is a less satisfactory basis for the fixed charge as it may be influenced by the political situation, and in consequence may fluctuate.

Mr. E. G. Taylor: In view of the increasing popularity of the domestic load it seems evident that before very long the ordinary lighting tariff will disappear, and in consequence there will be a loss of revenue to distribution undertakings. Further, with the continued increase in the domestic load, the low tariff that we at the moment enjoy may be affected, as the domestic load tends to become more important than the power load. I should like to know what Mr. Handley has to say about this; is the present domestic tariff likely to rise or to fall?

Mr. C. F. Davey: In certain districts the two-part tariff system is in operation, coupled with a clause which states that the consumer must guarantee to pay a minimum consumption charge in addition to the fixed rateable-value standing charge. The two-part tariff system alone surely provides sufficient encouragement for householders to use more units, and it should not be necessary to force on them a minimum-consumption guarantee.

Mr. V. L. Farthing: I should be glad if Mr. Handley could give some idea of the tariffs available for electric boilers.

In my opinion the cost of the clerical work involved in operating complicated tariffs must amount to a fair proportion of the charge to the consumer.

Mr. W. Parry (Liverpool): The object of the two-part domestic tariff is to encourage the consumer to take a load which will be remunerative to the supply authority. It seems to me, however, that the usual bases for the fixed charge are not closely enough related to the individual consumer's requirements or his pocket on the one hand, or, on the other, to the cost of his load to the supplier. Assessments vary from one district to another, and a consumer in a central district, probably close to the source of supply, may, owing to a high assessment, pay more for a given load than one in an outlying district with a low assessment, and the cost of supply is probably heavy in this case owing to distribution charges. Again, floor area is not always a reliable indication of the consumer's needs: a large old-fashioned house may have lofty rooms requiring more heating, or, on the other hand, some rooms may only be used occasionally. The important matter for the consumer is the sum he is prepared to pay for a given electrical service, whilst, for the supplier, maximum demand is a vital item, especially at peak hours.

These considerations appear to me to suggest a tariff under which a consumer would contract to pay a fixed sum for a given maximum demand, irrespective of assessment, floor area, etc., and dependent only on his requirements or his purse. The maximum-demand system as applied to industrial consumers would be too costly and complicated for domestic loads, and I have in mind a system incorporating a current-limiting device which would give the consumer some warning that he was approaching his maximum, all units in excess of which would be charged for at a high rate. Or perhaps if the supply were interrupted, or made ineffective by the insertion of a series resistance, on the maximum being reached, meters and much clerical expense might be dispensed with entirely.

I think consumers would soon adapt themselves to a household routine which would appreciably even out their load over the 24 hours. In my own case, with a total annual consumption of about 9 000 units, the demand may vary between 0 and 10 kW, with cooker, water heater, and radiators. I could probably keep my maximum down to 5 kW without serious inconvenience, if there were sufficient inducement, and would gladly do so if I could, without extra cost, take 2–3 kW throughout a winter night for greenhouse heating, which at present is too expensive at 0·625d. per unit. A large number of consumers adjusting their loads to their limit figure in this way would be of great benefit

to the supply authority, and I think that after a transitional educational period the latter would be enabled to reduce substantially the all-in cost to consumers, or, conversely to increase their remunerative load.

Mr. B. Handley (*in reply*): I agree entirely with Mr. Thwaites's statement as to the fundamental conditions for sound tariffs. With regard to his query as to experience with two-part prepayment meters, my own view is that if the undertaking is operating a two-part tariff upon any basis, the prepayment meter should carry out the functions of collecting the money strictly upon the basis adopted. For practical purposes there should be some limit to the arrears of fixed charges which may be collected, although I do not agree that none should be collected. A fixed-charge collector has been found very suitable by a number of undertakings.

Mr. Waygood very properly emphasizes that simplicity must be the keynote of a two-part tariff.

I agree with Mr. Taylor's statement that the flat-rate lighting tariff will tend to disappear. In fact it has become of no great importance so far as domestic dwellings are concerned in a number of supply areas. If the domestic load ever becomes predominant, the incidence of the maximum load may of course lead us to make some revision of our charges.

There is much to be said for Mr. Davey's point that the standing charge of a two-part tariff should not be coupled with a minimum-consumption guarantee.

Electric boilers, which Mr. Farthing mentions, are now being supplied at rates varying from 0·18d. to about 0·33d. per unit. Undoubtedly complicated tariffs must increase office costs, which the consumer has to pay. This is a further reason for simplicity of tariffs.

Mr. Parry mentions the point which has so often been raised, that neither the size-of-house system nor the rateable-value system can be defended as being a logical basis for the two-part tariff. This is quite true, but I suggest that his remedy is also illogical in that it takes no count of the time of the system peak.

The chief asset of the size-of-house or rateable-value system is its simplicity, and its appeal to the consumer. Another point to be remembered is that once a consumer has adopted the two-part tariff, and as he increases his consumption, the actual basis of the standing charge becomes of less importance in affecting the average price per unit which he has to pay.

DISCUSSION BEFORE THE WEST WALES (SWANSEA) SUB-CENTRE, AT SWANSEA, 28TH JANUARY, 1937*

Mr. R. Richards: I am strongly of the opinion that rateable value is not a fair basis for the standing charge to be paid by a consumer. I give the following reasons for my criticism of it: (1) The assessment of a property is no guide to the size of house and therefore to the potential consumption of energy. The assessment depends on position and locality. (2) Property in the newer-developed areas of a town is often assessed lower than in the centre of the town, and thus the standing charge will be lower, although the transmission costs are actually higher. (3) In the quinquennial revision of assessments the rateable value may be increased, causing an automatic increase in the standing charge, as happens in connection with water rates now in many cases.

I favour either a maximum-demand system with a fixed charge per kW and small charge per unit consumed, or a steeply graded sliding scale.

Mr. T. Stevens (*communicated*): While cheap electricity might be obtainable by any domestic user in Herne Bay who consumed as much as the author generates for his home, namely 8 000 units in a year, the latest returns tell a very different story for the people who live there. The figures are:—

Population of Herne Bay, 17 000.
Number of consumers, 2 311.
Units sold per consumer for light, heat, and cooking (1934), 364.
Units sold per consumer for power, 63.
Units sold per consumer for public lighting, 30.
Total units sold per average consumer, 457.

No other town in Kent is charged at 8d. a unit for light and 4d. for other uses. Before I came to Herne Bay my home consumption exceeded 7 000 units a year at a total cost of 1¼d. a unit, but in Herne Bay it is 320 units.

In many areas half of the population are only small users and cannot benefit by a two-part tariff because they do not want to increase their expenditure on electricity to the extent necessary to make such a tariff an advantage.

I have drawn up Table A in order to disprove the statement which is frequently made that a complete change-over from flat rates to a two-part tariff would deplete the revenue of an undertaking. Table A gives the units sold by the undertaking in question in the year before a two-part tariff was available, together with the respective rateable values (R.V.), floor areas, and average price per unit, and the year's revenue. My data for column (8) in Table A being limited, I cannot give real averages; in Table B I therefore give limits based on areas of single-consumer premises and the corresponding rateable values.

The two two-part tariffs adopted result (except for consumers having rateable values of £20) in revenues, for all services, which are well above the figure given by the flat rate for lighting for a consumption of the average number of units used in the year before there was a two-part tariff. A consumer taking less than the average saves money by using flat rates.

I should like to know what advantage is obtainable from any two-part tariff which cannot be given by a stepped tariff making charges uniform for all users of equal amounts, and free from all complications. The stepped tariff can have as low a final rate as the two-part tariff, and is far less bewildering to the consumer.

Tariff No. 4 is one which the lowliest housewife can understand easily, and is of the type which has been proved successful by many important undertakings. It is suitable for every supplier now charging more than 6d. a unit.

* Only the paper by Prof. Miles Walker ("The Prices for Electric Supply") was discussed at this meeting.

Table A

AVERAGE COST PER UNIT SOLD, ASSUMING ALL ADOPT ANY ONE TARIFF

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)		(9)	(10)
Total consumers in each R.V. group	Limits of rateable values for each group of consumers	Units sold to average consumer in the year before 2-part tariff No. 1 was available			Tariff No. 0 (for comparison), 15 % on R.V. and 1d. per unit	Tariff No. 1 (adopted 1933), 25 % on R.V. and 1d. per unit	Tariff No. 2* (adopted 1934)		Tariff No. 3, 6d. light, 3d. power, 1d. heat†	Tariff No. 4‡
		Light	Power	Heat			(a)	(b)		
	£				pence/unit	pence/unit	pence/unit	pence/unit	pence/unit	pence/unit
233	4–20	129	58	9½	3·76	5·6	4·1	5·3	4·87	6·3
413	21–30	110	3½	22½	7·45	12	7·2	12·3	5·09	6·43
555	31–40	170	16¼	12	7·55	11·9	7·1	11·2	5·45	6·3
561	41–50	214	19½	3	7·15	11·2	7·3	10·4	5·18	6·23
413	51–60	277	51½	29½	6·59	10·3	7·3	9·4	5·16	6·01
186	61–70	288	36	56½	7·15	11·2	6·9	10·1	4·98	5·95
226	71–80	440	68½	25¾	6·06	9·4	7	8·4	5·38	5·61
139	81–100	490	110	56	6	9·3	7	8·1	5·07	5·32
189	101–150	834	89	115	5·23	8	6·8	6·9	5·17	4·69
2 915	4–150	268	38	32	6·26	9·9	7	9	5·2	5·75
Year's total revenue (£)					25 750	40 708	28 767	36 986	21 370	23 566
Compared with tariff No. 3					120 %	190 %	134 %	185 %	100 %	110 %
Compared with tariff No. 4					110 %	173 %	122 %	157 %	90 %	100 %

* A floor-area charge of ¾d. per sq. ft. per annum (800 sq. ft. minimum), plus 1d. per unit. For each additional 100 sq. ft. add 0·6d. per sq. ft. up to 1 800 sq. ft., and 0·48d. per sq. ft. above 1 800 sq. ft.

† Three meter rents extra.

‡ 6s. each quarter in summer (this includes meter and 10 units of electricity). 9s. each quarter in winter (includes 15 units). 6d. per unit for additional units up to 75 in a quarter. 5d. per unit for additional units 76–125 per quarter. 4d. per unit for additional units 126–250 per quarter. ½d. per unit for additional units over 250 per quarter. It should be noted that this tariff complies with Section 19 of the Electric Lighting Act of 1882, but two-part tariffs do not comply.

Three tariffs, equally simple, quoted on page 523 of vol. 79 of the *Journal* (1936), if applied to the consumption in the Table give the following costs:— Tennessee Valley, 1·65d./kWh; New York City, 3·15d./kWh; Southern Canada Power Co., 1·74d./kWh.

Table B

Floor area (sq. ft.)		Rateable value (£)
Col. 8(*a*)	Col. 8(*b*)	
1 200	2 500	25
1 800	3 500	35
2 800	4 500	45
4 000	5 500	60
6 000	7 500	74
7 500	9 000	91
12 000	—	120

Prof. Miles Walker (*in reply*): In reply to Mr. Richards, I would point out that if the consumer were given the option of having his standing charge based either on the rateable value or on the size of the house, and if these standing charges were worked out on an equitable basis, the objections that have been raised against the rateable-value method would disappear. It would then be employed in equitable cases and we should have the advantage of its great simplicity.

The figures given by Mr. Stevens are very interesting. One is surprised to see that the average price works out at such a high figure, even under the more recent tariff. This must surely be because the consumers have failed to make use of the small charge per unit and still have their bills swamped by the fixed charge.

DISCUSSION ON "THE EFFECTS OF IMPULSE VOLTAGES ON TRANSFORMER WINDINGS"*

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 15TH DECEMBER, 1936

Mr. H. V. Field: The authors' demonstration outfit would be extremely useful to technical colleges and research organizations engaged in the study of impulse phenomena. One interesting point noted from the oscillograms is that there is no voltage-rise at the line end of the transformer: surely a rise in voltage due to reflection of the incident wave is to be expected at that point.

In the case of impulses applied simultaneously to both ends of a transformer winding, have the authors made any tests or measurements to determine whether the oscillograms of voltage variation at any point are the same as would be obtained by superimposing the oscillograms obtained by applying impulses to each end of the winding in turn?

It is noticed that in the case of impulses having a long tail the voltage oscillations set up in the winding are much greater than those obtained with impulses having a short tail. Can this be ascribed to the greater energy associated with the former type of impulse?

On page 119 it is pointed out that distributed earth capacitance is the principal factor causing concentration of stress across the winding at the line end. This is decidedly different from the effect of earth capacitance concentrated at the line terminal, where it relieves the end-turn stresses by reducing the steepness of the wave-front of the impulse transmitted to the winding as compared with that of the incident wave.

Mr. N. C. B. Carrick: I am interested to find the Heaviside unit function coming into consideration again. It is yet another illustration of a mathematician working in the dark and yet some years later revolutionizing the whole of an industry.

It seems to me difficult to visualize the physical reality of $C_g C_s$, particularly while the lines of electrostatic field are changing rapidly as a surge passes through the transformer. With the repeated surges demonstrated, does the effect of one die away completely before the next is applied? I ask this, because I noticed a waviness of the baseline with some of the long-tailed surges shown.

I should like Dr. Allibone to give us a short description of the working of the repeated-surge-impulse generator with which he demonstrated on the cathode-ray oscillograph.

Mr. J. M. Gibson: The authors' subject is one in which we are very much interested in this district. I have been trying to visualize the results on the secondary side of a transformer due to a lightning surge where the phases on the high-voltage side are unearthed except at the generating-station earth, and where the mid-point of the low-voltage winding is rather doubtfully earthed: what will be the conditions on the low-voltage network? We have had several examples of lightning doing damage to low-voltage apparatus in such circumstances, and we have tried to suppress such an influence, in some cases on particular services where damage has been done and in other cases by putting in suppressors at the transformer low-voltage terminals. It would appear that to put in suppressors at the terminals may be beneficial.

Dr. Allibone mentioned in his opening remarks that it was only about 1920 that it was found necessary to make these investigations, but I can assure him that as long ago as 1906 we experienced difficulties with switching surges. We had to disconnect transformers before we dared switch in the lines. I am sure we could have very well done with the knowledge these investigations have produced, 10 years before they were commenced.

Mr. J. H. Haws: There is one aspect of the authors' subject on which I should like further information. Now that this work has been done, what will be the effect on transformer design? It appears that the surge voltage affects the whole of the winding and, as the voltage is said to be considerable, it appears necessary to insulate the whole of the windings accordingly. It is doubtful whether it is a practical proposition to insulate a transformer winding to that extent, and it appears that it is not permissible to allow a surge to enter the transformer. It will therefore be necessary to apply some device to the transformer terminals.

[The authors' reply to this discussion will be found on page 589.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 25TH JANUARY, 1937

Mr. C. G. Giles: Although the mathematical formulae for determining the distribution of voltage through a transformer winding when a travelling wave reaches a line terminal has been known for many years, it is only within recent years that apparatus in the form of the cathode-ray oscillograph has been available to record the very high-frequency oscillations that can occur within the windings. By means of this apparatus it is possible now to examine visually the effect of surges applied to a transformer under all operating conditions in a very short space of time, and to study the effects of modifications to design.

I should be glad if the authors would state the kVA rating of the two-legged core-type transformer described in Section 3(*a*).

It appears that the fundamental period of oscillation

* Paper by Messrs. T. E. ALLIBONE, D. B. MCKENZIE, and F. R. PERRY (see page 117).

is of the order of 50 microseconds for the oscillograms on pages 127 and 131, while it is about 25 microseconds for the oscillograms on pages 129 and 136. From this I infer that the two sets of oscillograms are taken on different transformers.

The authors mention that oscillograms may be obtained of the voltage across sections of the winding. As no actual records are shown in the paper I should like to include one from a set of tests that I have carried out

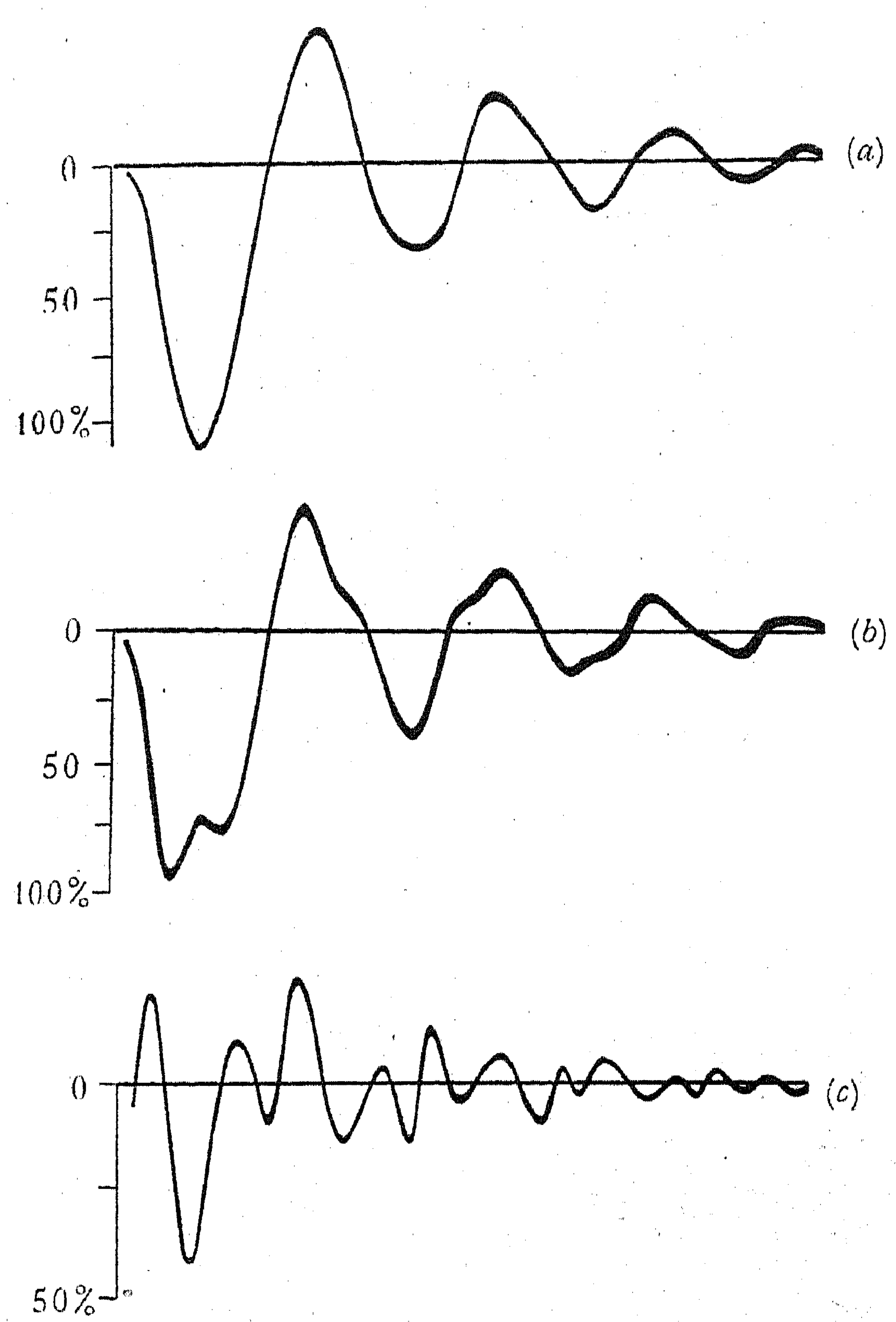


Fig. W.—Oscillograms of voltages measured between two tappings on the high-voltage winding of a 20-kVA single-phase transformer, and from the same two tappings to earth, using a 1/70 wave.

(a) Voltage at 50 % tap.
(b) Voltage at 75 % tap.
(c) Voltage between 50 % and 75 % taps.

on a 20-kVA single-phase transformer. Fig. W is a record of the voltage between the 50 per cent and 75 per cent tappings from the line end and also the voltages to earth from the same two tappings. The voltage across a large section of the winding has been chosen purposely to show more clearly the differential voltage at the two tappings.

The question is asked sometimes as to whether the voltage distribution through a transformer varies with the polarity of the applied impulse. The voltage distribution at low impulse voltages is the same for both polarities, as can be seen in Fig. X, which is a typical record of the oscillations in a transformer for a positive and a negative impulse of the same value applied in turn to the transformer.

With impulses approaching the breakdown value of a transformer it is possible that the voltage distribution in the two cases may be slightly modified owing to the difference of corona effects. I should be glad to have the authors' views on this point. In passing, the relatively slow period of oscillation of the transformer on which this record was obtained, as compared with those obtained on the authors' transformers, should be noticed. The distinction is of course due to the fact that the constants of the various transformers are different.

Mr. J. A. Harle: It is only since the technique of impulse testing has developed and since the high-speed cathode-ray tube has become an efficient tool that a practical approach to the problem discussed in the paper has been possible. It is extremely interesting to note that the initial voltage distributions during a surge closely confirm the old theoretical arguments and that the later distributions indicate how the length of wave-tail gives different voltage distributions. This, I think,

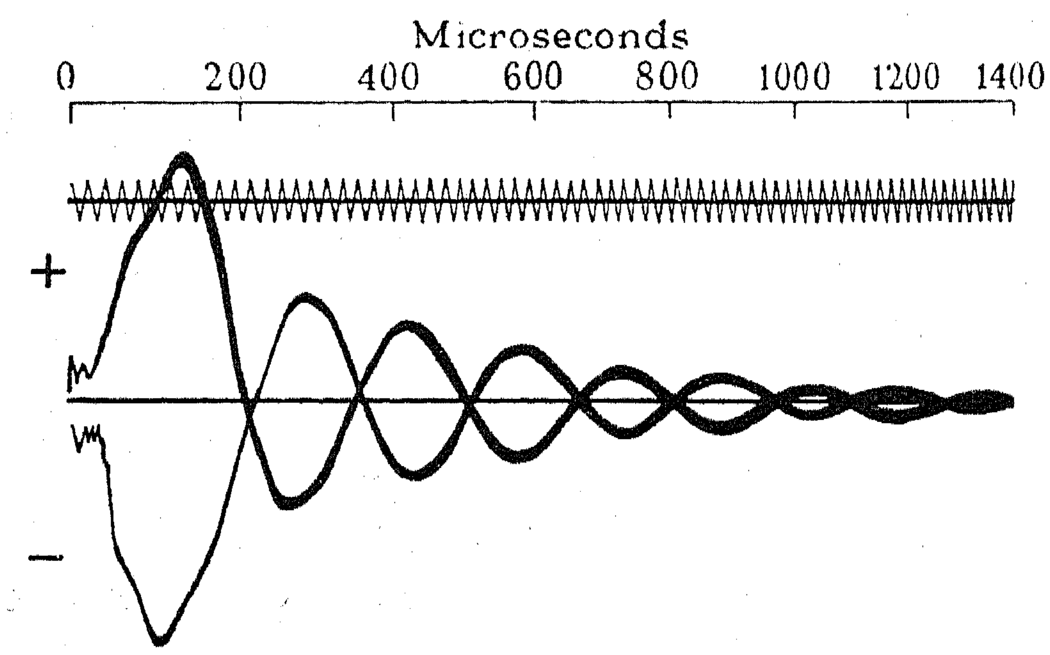


Fig. X.—Oscillograms of voltage in a transformer for a positive and a negative 1/70 wa[illegible]. Neutral of high-voltage winding earthed.

will explain between-turn failures in transformers where portions of the winding other than the reinforced end-turns have broken down.

Researches of this kind will all assist in the production of transforming equipment that can be connected directly to overhead lines, and such apparatus will be designed to withstand surges whose magnitude is controlled by the impulse flashover value of the overhead lines. It will have to be realized that the price of such apparatus will be increased depending upon the impulse flashover voltage of the line.

Fig. 26 gives an extremely interesting example of the transmission of a surge from one winding to another, and tends to indicate that bulk feeds into underground distribution systems via overhead lines and step-down transformers may produce voltage surges into systems which had previously been practically immune from them.

It would appear necessary that not only should the high-voltage gear associated with the overhead line have an adequate impulse-voltage rating but also the gear associated with the low-voltage network should have an adequate impulse rating based on the degree of transmission that can exist.

I agree with the authors regarding the inadequacy of the V.D.E. and S.E.V. tests, as indicated on page 142.

I have always regarded these as proving the insulation to be adequate under arcing-earth conditions rather than under impulse conditions, but I should appreciate the authors' views on this aspect of the test.

Mr. M. Waters: It would appear that, owing to the very much greater resistance of the windings, any oscillations which may occur in an instrument transformer will be damped out very rapidly and will be comparatively harmless, although the initial voltage distribution will be similar to that in a power transformer. The damping for a given transformer is determined by the value of q in equation (14), and for purposes of comparison q may be regarded as proportional to the ratio (resistance/reactance) at power frequency, with a sufficient degree of accuracy. For a 33-kV instrument transformer this ratio will be of the order of 2 : 1, and for a small power transformer of the order of 1 : 4. Thus the value of q will be about 8 times as large for the instrument transformer as it is for the power transformer, and the oscillations will be very rapidly damped out.

Mr. Edgar J. Williams: As the present paper shows and as is already known, impulse voltages produce exceptional stress in transformer windings (1) between windings and earth, (2) between turns. The voltages to earth are of the same order as the applied impulse voltages, whereas the stresses between turns due to impulses may be of the order of the working voltages, i.e. several hundred times the normal inter-turn stresses. The question of proportioning the end turns to withstand these excessive stresses is the chief problem in connection with the effects of impulse voltages on transformer windings.

Experiments carried out on complete transformers tested to destruction by impulse voltages indicated that, apart from the use of end rings or other shields for controlling the electrostatic field in the neighbourhood of the end turns, two conditions had to be fulfilled: (*a*) The end-turn insulation had to be finely graded, as mentioned in the paper. (*b*) The extra insulation added had preferably to have a high permittivity. By observing this second condition the constant called α in the present paper was reduced and a more favourable distribution of the impulse voltage along the winding secured.

Those who have examined the characteristic breakdown produced by impulse voltages will appreciate the difficulty of detecting the damage thus caused. It was no doubt with this difficulty in mind that the authors put forward the arrangements shown on page 142. Another well-known means of trying to show up breakdowns due to impulses is to carry out the surge tests with the transformer excited to normal voltage and to synchronize the impulses with the peak of the power-frequency wave of appropriate polarity. The effectiveness of this last measure is open to doubt.

Apart from breakdowns to earth, we may divide breakdowns in transformer windings due to impulse voltages into three classes, namely (i) breakdowns between adjacent turns, (ii) breakdowns between turns in adjacent layers, (iii) breakdowns between turns in adjacent coils.

With medium and large transformers the normal power-frequency voltages in classes (ii) and (iii) are probably sufficient to cause a power arc to follow up the impulse breakdown in all cases. In class (i), however, even in large transformers the voltages between turns are so moderate that it is questionable whether they can cause the power arc to follow up. Exciting the transformer to normal voltage will therefore not help in detecting damage done by surges to the inter-turn insulation. Until such damage can be detected with certainty, impulse tests must be accompanied by a certain amount of risk to the complete transformer.

THE AUTHORS' REPLY TO THE DISCUSSIONS AT MIDDLESBROUGH AND NEWCASTLE

Dr. T. E. Allibone and **Mr. D. B. McKenzie** (*in reply*): Several speakers have asked for a description of the recurrent surge generator used in our demonstrations. Such a description is outside the scope of the paper, but an article on the instrument is about to be published by Mr. G. S. Scoles in the electrical Press.

Mr. Field should note that the oscillograms of the applied voltage are all recorded at the transformer end of the cable, so that such records include the reflection of the wave initially entering the delay cable shown in Fig. 7. All records within the winding are shown as percentages of the voltage actually appearing at the line terminal. When impulses are applied at both ends simultaneously, the oscillograms are only approximately the same as would be obtained by superimposing the oscillograms obtained by applying impulses to each end of the winding in turn. This approximate agreement may be due to the finite value of the wave-tail; to give experimental proof of the exact equivalence would necessitate the use of very long wave-tails. A reduction in amplitude of oscillation due to short wave-tails may be ascribed to the smaller energy of the short wave-tailed impulse; but a better view is to consider the implications of Equation (12).

Damage in low-voltage circuits due to transference from high-voltage windings is not at all uncommon. The chief safeguard to low-voltage circuits is the extensive cable network often connected to the transformer on this side; but, in the absence of such network, voltage suppressors should be used and will prove beneficial.

In reply to Mr. Haws, the effects of these and similar researches on transformer-winding design are threefold:—

(*a*) Attention is given to major insulation between windings and to intercoil insulation on a strictly quantitative basis, working from a knowledge of voltage distribution and of impulse strength of the insulation materials employed.

(*b*) Attention is given to special features of design, end-rings, cross-over connections, voltage regulators, internally-fitted bushings, change-over link mechanisms, etc.

(*c*) Attention is given to winding details when the impulse strength of coils, blocks, and sheets, can be improved by suitable study.

As transformers in general have given good service already in the field, the above three avenues of progress

are calculated to remove those defects still responsible for what few failures do occur.

With reference to Mr. Giles's remarks, the coils of the model transformer described in Section (3a), as stated in the second paragraph on page 122, are suitable for a 37-kV limb, and our remarks on page 172 in reply to Mr. Stigant deal with the points raised in Mr. Giles's third paragraph. We have no reason to doubt that the distribution of voltage in the winding is the same positive as on negative polarity, even at high voltages

We agree with Mr. Harle's view of the V.D.E. tests Mr. Waters's conclusion is correct. In addition, would draw his attention to our remarks on page 3 in reply to Mr. Nuttall, and Mr. Williams's attenti to our remarks on impulse testing of transformers page 141.

INSTITUTION NOTES

OVERSEAS MEMBERS AND THE INSTITUTION

During the period 1st January to 30th April, 1937, the following members from overseas called at The Institution and signed the "Attendance Register of Overseas Members":—

Bennett, A. P. M. (*Athens*).
Chakravarti, S. P., M.Sc. (Eng.) (*Lucknow*).
Crawford, J. M., M.B.E. (*Sydney*).
De Silva, W. E. (*Colombo*).
Martin, E. M. (*Adelaide*).
Pilgrim, G. J., B.Sc.(Eng.) (*Cape Town*).
Samson, M. (*New Delhi*).
Thrupp, W. F. (*Madras*).
Tremain, W. E. (*Buenos Aires*).
Unwin, D. J. (*Colombo*).
Waite, F. J. G. (*Lahore*).
Welman, D. P. (*Colombo*).
Weerasena, D. de Silva (*Colombo*).

TEMPORARY REGULAR COMMISSIONS IN THE ROYAL ENGINEERS

A further offer (see *Journal* No. 480, December 1936, page 686) of temporary commissions in the Royal Engineers is being made to members of the Institutions of Civil, Mechanical, and Electrical Engineers. Prospective candidates, who should have reached the age of 21 years and be under the age of 27 years on the 29th August, 1937, can obtain full particulars on applying to The Under-Secretary of State (A.G.7), War Office, London, S.W.1.

GRADUATESHIP EXAMINATION RESULTS: NOVEMBER, 1936 (SUPPLEMENTARY LIST)*

Passed†

Agent, Kaikhashru Dhanjishaw (*India*).
Ainger, Harold (*New Zealand*).
Amin, Rambhai Purushottamdas (*India*).
Baharee, G. S. (*India*).
Bahree, Naresh Chand (*India*).
Barker, Robert Henry (*India*).
Bhattacharjee, Hemendra Kumar (*India*).
Blacklaws, Alexander Bothwell (*South Africa*).
Brendish, Clarence Edward (*India*).
Brown, Ian Harvey (*New Zealand*).
Bryce, John Francis (*New Zealand*).
Butail, Roshan Lal (*India*).

* See page 232.
† This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Passed—continued.

Chandra, Avinash (*India*).
D'Costa, Arthur Evarist (*India*).
Desai, Thakorlal Muljibhai (*India*).
Deva, Yash Paul (*India*).
Hughes, Stanley Owen (*New Zealand*).
Kharas, Hormusji Bhikhaji (*India*).
Kitchens, Harold (*Gibraltar*).
Lawton, Charles Tinsley (*South Africa*).
Lingappasastry, Mukkavalli (*India*).
Maclachlan, Ian Neil (*New Zealand*).
McNair, Ian Bruce (*New Zealand*).
Madgavkar, Madhav Anandrao (*India*).
Merrifield, Austin Randolph (*South Africa*).
Mohamed, Obaidulla Hidayetulla (*India*).
Munsiff, Jamshedji Pohchaji (*India*).
Padhye, Pandurang Anant (*India*).
Parange, Shantaram Gajanan (*India*).
Patel, Rustom Ratanshaw (*India*).
Pereira, Allan Conrad Harry (*Ceylon*).
Ramanathan, Kaveripatnam Natesa (*India*).
Randhava, Balram Singh (*India*).
Saeed, Sheikh Mohd (*India*).
Sarma, Rama Kanta (*India*).
Scott, Colonel Conroy (*South Africa*).
Shah, Manubhai Damodardas (*India*).
Shanks, William James (*New Zealand*).
Sheikh, Rafiq Ahmad (*India*).
Simpson, Ronald Mawson Oglesby (*South Africa*).
Subrahmanyam, Dharmavadhani Krishnaiyar (*India*).
Subrahmanyam, Josyula (*India*).
Subrahmanyam, P. N. (*India*).
Subramanian, V. M. (*India*).
Tandon, Manohar Lall (*India*).
Theobald, Stanley (*South Africa*).
Vaidyanathan, Anantanarayana (*India*).
Valladares, George Felix (*India*).
Verma, Rattan Chand (*India*).
Williams, Alfred Henry (*South Africa*).
Williams, Kenneth Frank (*India*).
Wise, Norman (*Nigeria*).

Passed Part I only

Ahluwalia, Gurbakhsh Singh (*India*).
Ananthanarayanan, Chittur Seshaier (*India*).
Bambery, Colin McIntosh (*New Zealand*).

Passed Part I only—continued.

Banerji, Dhirendra Nath Bandyopadhyay (*India*).
Bates, Maharaj Krishan (*India*).
Betts, Frederick Francis (*New Zealand*).
Borwankar, Dinkar Keshava (*India*).
Carlaw, Arthur Donald (*New Zealand*).
Dastur, Naval Jamshedji (*India*).
Daver, Framroje Pirojshaw (*India*).
Desai, Chhotubhai Ranchhodji (*India*).
de Villiers, Michael Arend Nelson (*South Africa*).
Dotivala, Hormuz Dadabhai (*India*).
Downey, James Arthur (*Victoria, Australia*).
Fernandes, Patrick (*India*).
Gaunt, Charles Nicoll (*South Africa*).
Gejji, Ramchandra Krishna (*India*).
Goldman, Henry (*South Africa*).
Hewett, Raymond Frederick (*South Africa*).
Homersham, Brian Ryder McClintock (*New Zealand*).
Jan, Ahmad Sheikh (*India*).
Karve, Keshav Raghunath (*India*).
Kell, George Leicester (*South Africa*).
Kondaswami, V. (*India*).
Krishnamurty, Chintalapaty (*India*).
Krishnaswamy, Vippodu (*India*).
Lal, Banke Behari (*India*).
Lodge, Ernest Charles (*South Africa*).
Madhavan, V. (*India*).
Malegamvala, Dinshaw Kaikhushroo (*India*).
Mande, Shrinivas Dinkar (*India*).
Morrison, John (*New Zealand*).
Mukerjee, Naba Krishna (*India*).
Murthy, Dodballapur Krishna (*India*).
Nair, Chandrasekhara Padmanabhan (*India*).
Padmanabhan, G. (*India*).
Pearson, John Archibald (*New Zealand*).
Ponnaiya, Vedachalam Arthur (*India*).
Prasad, Mukta (*India*).
Prasanna, Gorur Roysm Srinivasa (*India*).
Rajappa, S. V. (*India*).
Ramarao, Jata Venkata (*India*).
Rofe, Samual Charles (*New Zealand*).
Sahgal, Shiam Sunder Lall (*India*).
Seervai, Homi Pirojshaw (*India*).
Seth, Puran Anand (*India*).
Shanmuganathan, V. S. (*India*).
Sibal, Dev Parkash (*India*).
Siddappa, Byranna (*India*).
Smith, Ernest Leslie (*South Africa*).
Strachan, Thomas Alexander (*New Zealand*).
Thakraji, Nariman Pirojshaw (*India*).

Passed Part II only

Gardiner, John Henry (*New Zealand*).
Greer, Norman Campbell (*Western Australia*).
Jog, Balkrishna Laxman (*India*).
McCutcheon, Ian William (*New Zealand*).
Mahajan, Narayan Balwant (*India*).
Marathe, Kashinath (*India*).
Mill, Alexander (*New Zealand*).
Parakh, Adi Kaikhusru (*India*).
Ramarao, Kondury (*India*).
Toma, Robert (*Egypt*).
Turner, Young John Allen (*China*).

ELECTIONS AND TRANSFERS

At the Ordinary Meeting of The Institution held on the 22nd April, 1937, the following elections and transfers were effected:—

Elections

Member

Morehouse, Lyman Foote, B.S., M.A., D.Eng.

Associate Members

Brown, Alexander Blair.
Carson, Herbert Arthur.
Gill, Frederick William.
Henniker, Reginald Charles, B.Sc.(Eng.).
Higgitt, Harry Vernon.
Masson, Albert Henry.
Naylor, John Henry.
Redfearn, Sidney Warbrick, B.A.
Szu, Nelson, B.Sc.
Thomas, George Edwin T.
Thomson, Alexander.
Wilson, John Richardson, B.Sc.

Associates

Appleton, Maurice.
Dennes, Howard Gay.
Hawley, William George.
Lowe, Reginald Gretton.
Mardall, Evelyn George C.
Morris, Ernest Sidney.
Westlake, Albert Edward.

Graduates

Agent, Kaikhashru Dhanjishaw.
Ainger, Harold.
Amin, Rambhai Purushottamdas.
Baharee, G. S.
Bahree, Naresh Chand.
Barker, Robert Henry.
Blacklaws, Alexander Bothwell.
Brendish, Clarence Edward.
Brown, Ian Harvey.
Bryce, John Francis.
Caldicott, Richard Arthur H.
Darvill, Reginald William.
D'Costa, Arthur Evarist.
Elliott, William James.
Farmer-Green, Joseph Charles, B.Sc.
Gosling, Reginald Scrase.
Holmes, Frank Leslie, B.Sc.
Kelkar, Purushottam Kashinath, B.Sc., Ph.D.
Kharas, Hormusji Bhikhaji.
Kitchins, Harold.
Leith, Allan Ramsay.
Madgavkar, Madhav Anandrao, B.Sc.(Eng.).
Merrifield, Austin Randolph.
Miln, Peter McNab, B.Sc.
Morris, David John, B.E., B.Sc.
Munsiff, Jamshedji Pohchaji.
Murray, Donald Eaton.
Orr-Ewing, Charles Ian, B.A.
Padhye, Pandurang Anant.
Parange, Shantaram Gajanan.
Peck, David George.
Ramanathan, Kaveripatnam Natesa.
Reynolds, William James.
Shah, Manubhai Damodardas, B.Sc.(Eng.).
Shaw, William.
Sillars, Ronald William, B.A.
Sowry, John Humphrey M., B.Sc.(Eng.).
Subrahmanyam, Josyula.
Subramanian, V. M., B.Sc.(Eng.).
Tandon, Manohar Lall.
Theobald, Stanley.
Thomas, Geoffrey Mosley, B.A.
Thwaites, George Percy.
Toller, Ralph Northcote.
Valladares, George Felix.
Varley, Leonard John.
Walton, Henry.
Wise, Norman.
Wormell, Herbert Thomas, B.Sc.(Eng.).

Students

Fortune, Joseph Francis.
McCammont, Thomas.
McCombe, Charles George.
Mars, William John.
Permentiers, René Joseph.
Rice, Joseph.
Sinclair, William Donald.
Smith, George Christopher.
Watts, Roy James.
Zuckerman, Narcisse.

Transfers

Associate Member to Member

Baker, Eric William.
Elliott, Frederic James.
Horsley, William Douglass.
Kidner, Walter Elderton.
Lawrie, Thomas.
Neale, Roland Hayward R., Lieut.-Col.
O'Neill, Albert George.
Plowman, Reginald Cheyney.
Taylor, Ernest George, B.Sc.(Eng.).
Villiers, Algernon, M.A.

Associate to Associate Member

Brooks, John.
Cullen, Ernest Arnold.
Golds, Lionel Barton S.
Guilfoyle, Thomas James.
Johnson, Sydney Reynolds E.

Graduate to Associate Member

Attard, Anthony.
Bailey, George Edward, B.Sc.(Eng.).
Bamford, Thomas.
Brown, Andrew, B.Sc.
Caley, Leonard Percy, B.Sc.
Edwards, Harold George.
Irwin, Charles King.
Langfield, William Thomas.
Newman, Percy Laurence.
Rickards, Jack Tatham T.
Tanner, Ernest Basil T.
Thomas, Frederick John B., B.Sc.(Eng.).
Timmins, Frederick George, B.Sc.
Torrance, Alexander Edward.
Venables, Albert Henry.
Verity, Alfred Samuel.
Welch, John, B.Sc.
Whitehead, Maurice.
Williams, Hugh Jenkin.

Student to Associate

Roberts, David Bevan R.

The following transfers were also effected by the Council, at their meeting held on the 8th April, 1937:—

Student to Graduate

Aiyar, Subramani Ramaswamy, B.A.
Basu, Deba Prasad, B.Sc.
Bhattacharjee, Hemendra Kumar, B.Sc.(Eng.).
Brown, Allan Harry, B.Sc. (Eng.).
Butail, Roshan Lal.
Chandra, Avinash.
Chorlton, Arthur.
Darch, John Tait.
Desai, Thakorlal Muljibhai.
Deva, Yash Paul.
Duraiswami, Thozur Madabusi, B.Sc.(Eng.).
Golligher, Derek Garvin, B.Sc.(Eng.).
Grant, Alexander Cameron, B.Sc.
Gregory, John Pearson, B.Sc.(Eng.).
Gupta, Joy Deb, B.Sc.

Student to Graduate—continued.

Hanhart, Paul.
Harrison-Watson, Norman John.
Hughes, Stanley Owen.
Hutchison, William Milne, B.Sc.
Ingham, Arthur James.
Larsen, Peder William, B.Sc.(Eng.).
Lawton, Charles Tinsley.
Lingappasastry, Mukkavalli, B.A.
Maclachlan, Ian Neil.
MacLean, James Alexander, B.Sc.
McNair, Ian Bruce.
Mohamed, Obaidulla Hidayetulla.
Parmentier, Lewis.
Parton, John Edwin, B.Sc.
Patel, Rustom Ratanshaw.
Pereira, Allan Conrad H.
Perry, William Henry.
Piercy, Bruce.
Randhava, Balram Singh.
Ritche, John Bower.
Saeed, Sheikh Mohd.
Sarma, Rama Kanta.
Scott, Colonel Conroy.
Shanks, William James.
Sheikh, Rafiq Ahmad.
Simpson, Ronald Mawson O.
Slade, George Frederick, B.Sc.
Spencer, Philip Leonard, B.Sc.(Eng.).
Subrahmanyam, Dharmavadhani Krishnaiyar, B.E.
Subrahmanyam, Periyapatna Narasimhayya.
Swaffield, John, B.Sc.
Symonds, Alan.
Taitt, Stephen Edmund, B.Sc.(Eng.).
Thomas, Stanley Albert.
Vaidyanathan, Anantanarayana.
Verma, Rattan Chand.
Voss, John Edward F., B.Sc.(Eng.).
Waldock, Donald Albert G., B.Sc.
Walker, Thomas Geoffrey.
Watters, William Melville S.
White, Eric Lionel, B.Sc. (Eng.).
Williams, Alfred Henry.
Williams, Derek A. Hutton.
Williams, Kenneth Frank.
Wormall, John Bryan.

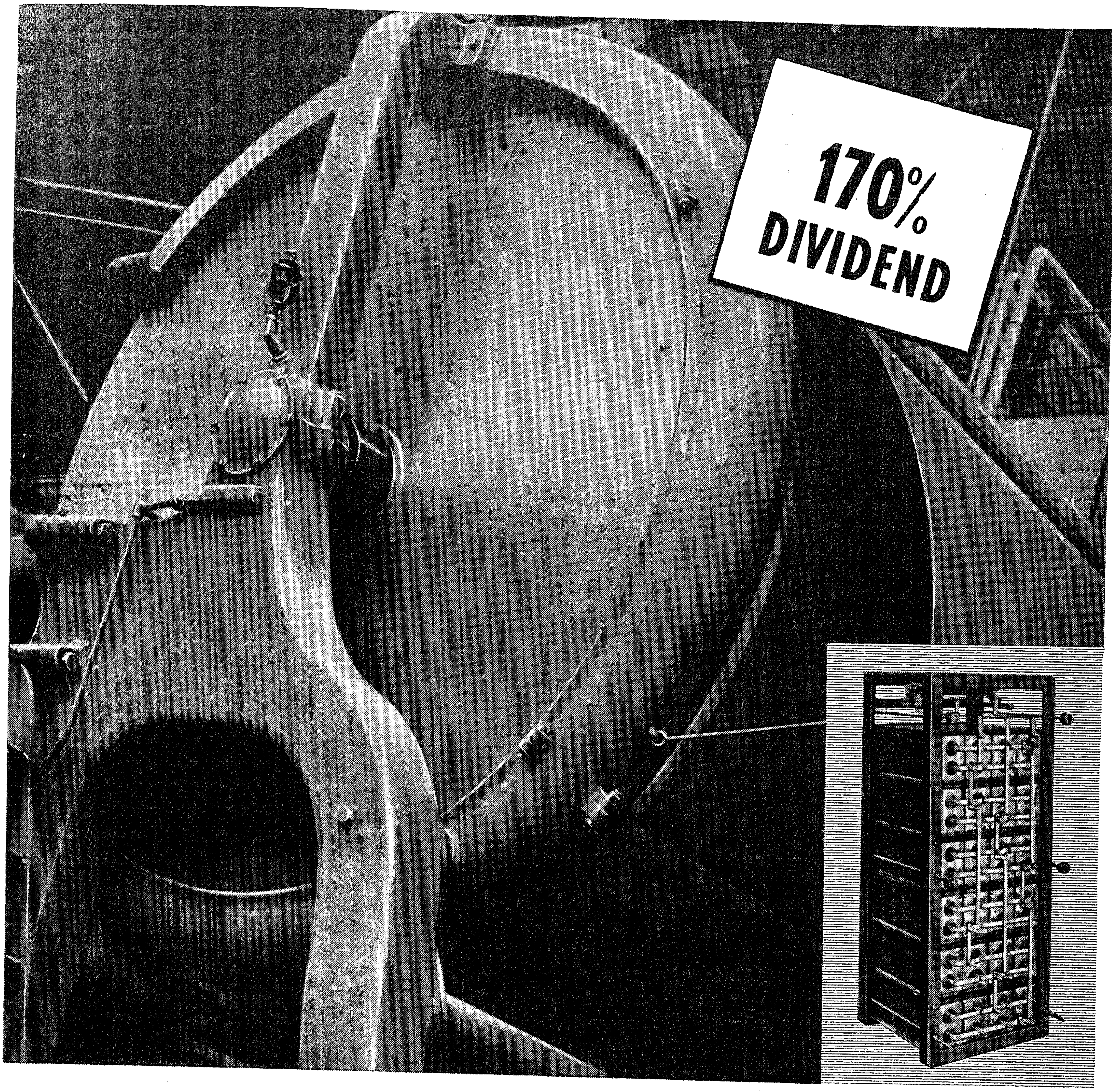
The following transfers were also effected by the Council, at their meeting held on the 22nd April, 1937:—

Student to Graduate

Anderson, Ronald Thomas W.
Douglas, John Bell.
Dunkley, Geoffrey Harington.
Eastwood, William Stuart.
Everitt, Laurie Harold R., B.Sc.(Eng.).
Gandy, Robert William.
Gaskell, Harold, B.Sc.
Gasper, Peter, B.Sc.(Eng.).
Harper, Frederick George S.
Jones, Frederick Charles.
Kram, Walter, B.Sc.
Manser, Robin, B.Sc.(Eng.).
Payne, Somers Leslie, B.Sc.
Ponnaiya, Vedachalam Arthur, M.A., B.Sc.
Read, Richard Alfred.
Salinger, Charles Moses.
Sandercock, Reginald Gilbert.
Shoubridge, Desmond Jack.
Thomas, Graham Isaac, B.Sc.
Tuff, Lawrence Forbes.

Photo—Aerofilms

Rytad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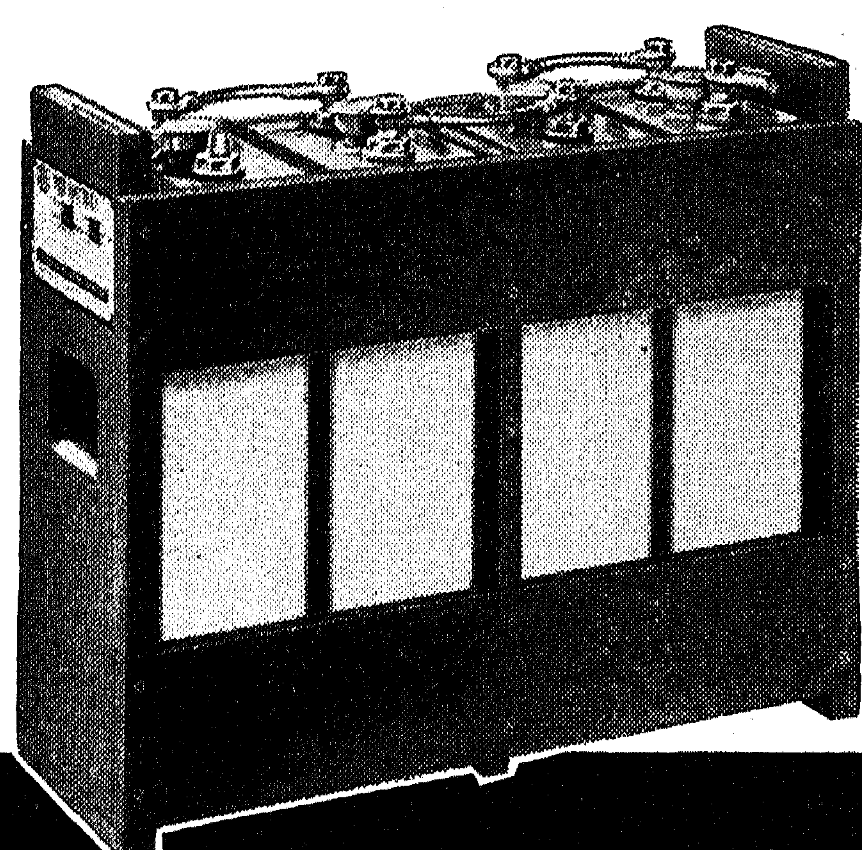

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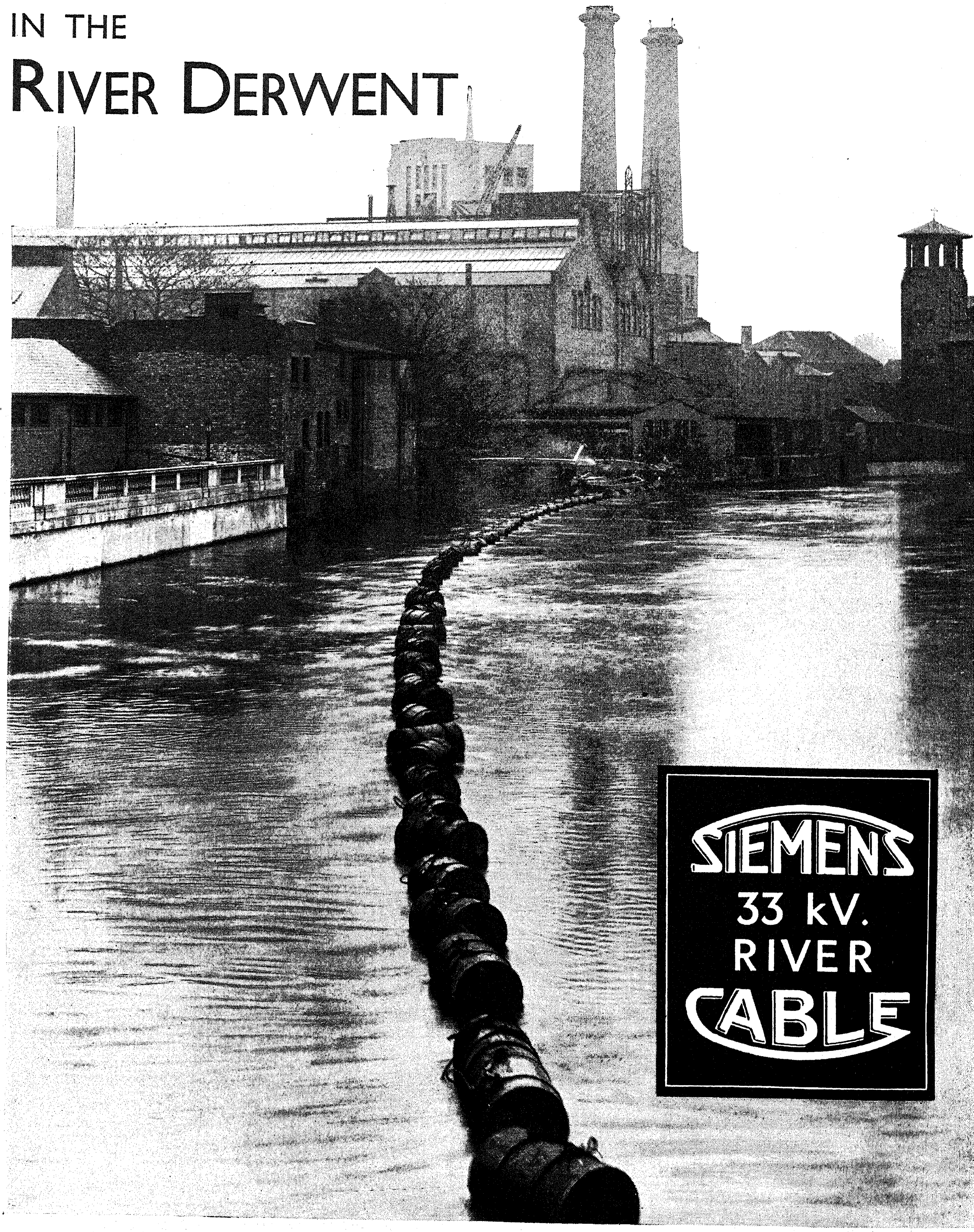
IN THE RIVER DERWENT



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